11th US NATIONAL CONGRESS
ON COMPUTATIONAL MECHANICS

Tailoring Topology Optimization to Composite Pressure Vessel Design with Simultaneous Consideration of Fiber Angle and Material Distribution

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Acknowledgments:

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Outline

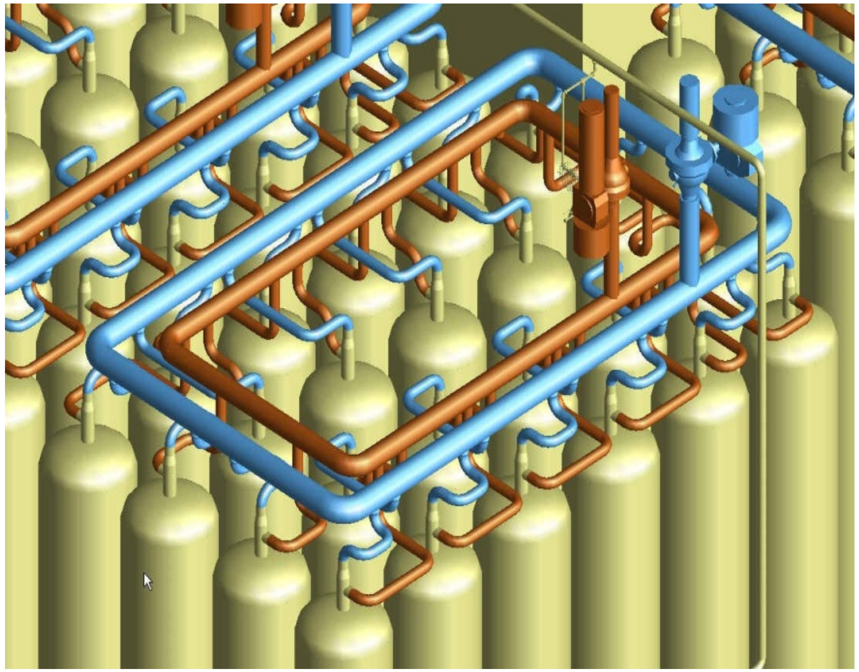
- Introduction
- Motivation and Objective
- Multilayer Composite Shell FEM
- Topology Optimization Method
- Design problem formulation
- Results
- Conclusions and future work

Introduction – CNG Pressure Vessels

Compressed Natural Gas (CNG) Pressure Vessels

CNG pressure vessels

CNG Cargo Containment System



CNG inside cars and buses

CNG – More attractive costs for compression, loading and unloading

Introduction – CNG Pressure Vessels

Comparison of CNG and LNG (Liquefied Natural Gas)

Size of investment for a 500MMscf/d plant

	CNG	LNG
Reserves:	Modest	Large
Processing cost:	MM$30-40	MM$750-2000*
Transportation costs:	MM$230/ship	MM$160/ship
Unloading costs:	MM$16-20	MM$500-550
Total investment:	$1-2 billion**	$2-3 billion**

* Depending upon the location of the production site

** Depending upon the number of ships used for the transport of the gas.

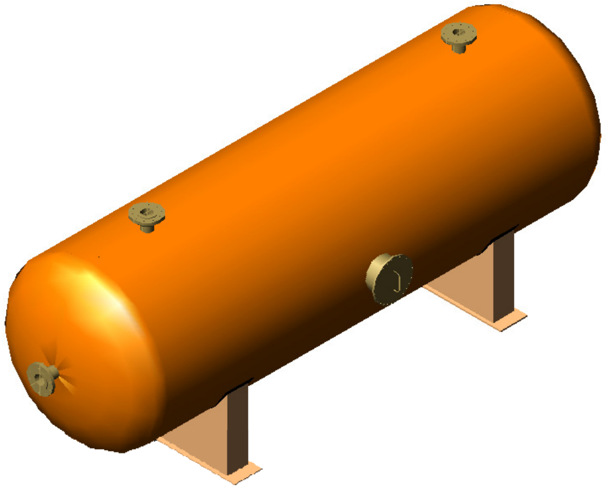
MMscf/d - million standard cubic feet per day

MM$ - million dollars

http://www.hebrewenergy.com/terms/

Introduction – CNG Pressure Vessels

Types of CNG Pressure Vessels



Homogeneous (stainless steel)

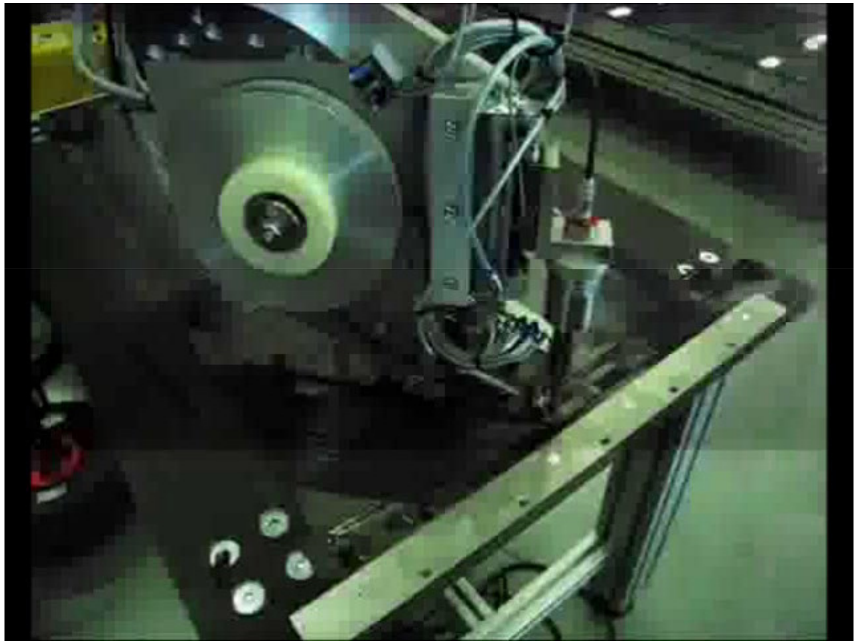
Composite CNG Vessels

Introduction - Motivation

Manufacturing Processes for CNG Pressure Vessels

Winding (traditional) – entire vessel layer has same fiber angle

Fiber Placement – same layer can have different fiber angles



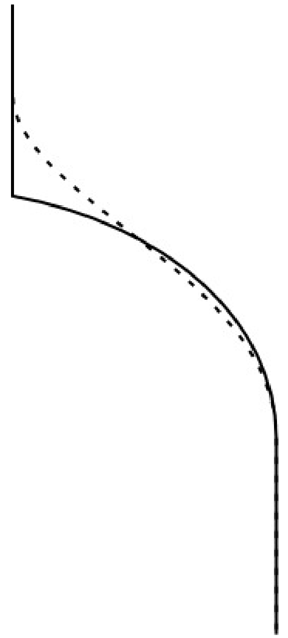
Fiber placement → it allows manufacturing of more complex composite vessel configurations with different topology and fiber angle distribution → topology optimization method

Introduction - Motivation

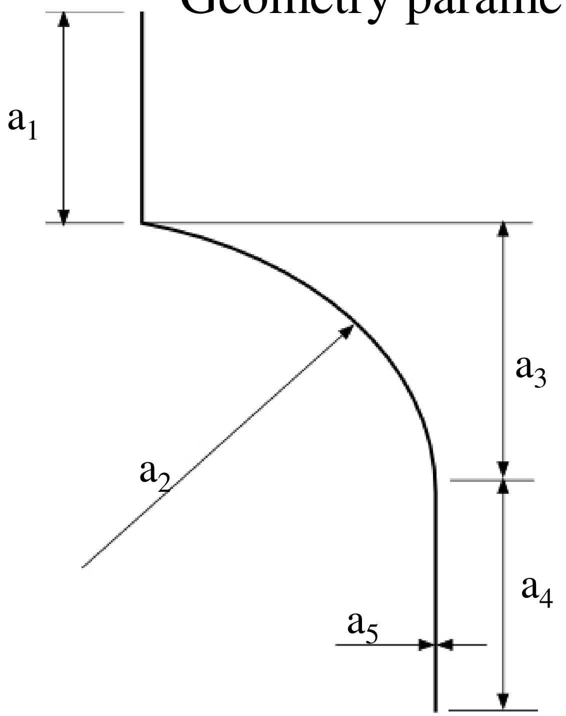
Costs of CNG vessel transport are too high → mass of gas/mass of vessel ratio is low → Optimization techniques can be applied to design pressure vessels in order to increase the 'mass of gas/mass of vessel' ratio. However, usually only parametric or shape optimization have been applied to improve the design of pressure vessels.

Introduction - Motivation

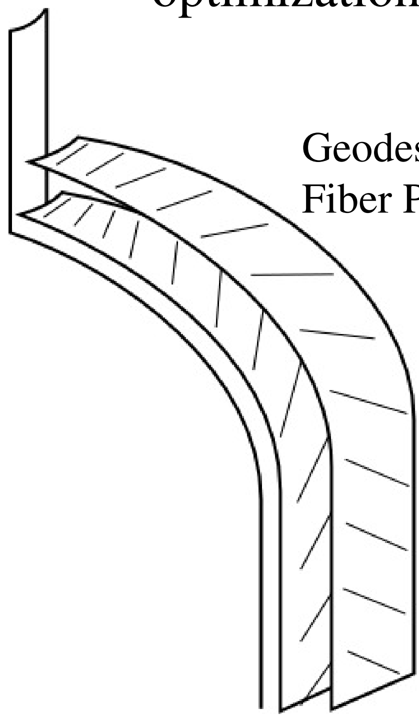
Shape optimization by splines



Parametric optimization Geometry parameters



Shape + Parametric optimization



- Homogeneous tanks: Zhu and Boyle 2000; Carbonari et al. 2011
- Topology nozzle optimization: Liu et al. 2001
- Composite tanks: Fukunaga and Uemura 1983; Vafaeesefat 2009; Kim et al. 2005

Winding → Geodesic Contour: Shortest path between two points on a surface → no slippage tendency between the fiber and the mandrel during manufacturing.

Objective

To develop a topology optimization formulation

for designing composite pressure vessels

considering the optimization of:

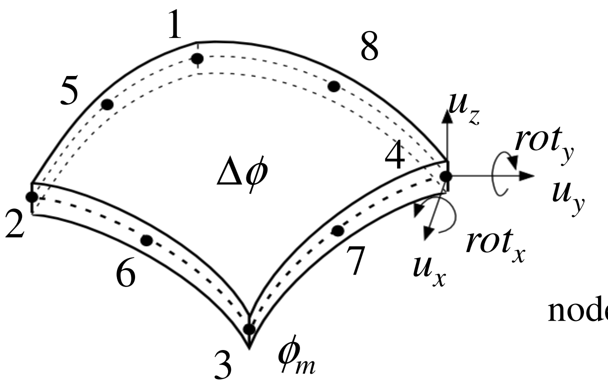
- Material Distribution
- Fiber local orientation

to minimize Tsai-Wu P-norm subjected to composite volume constraint.

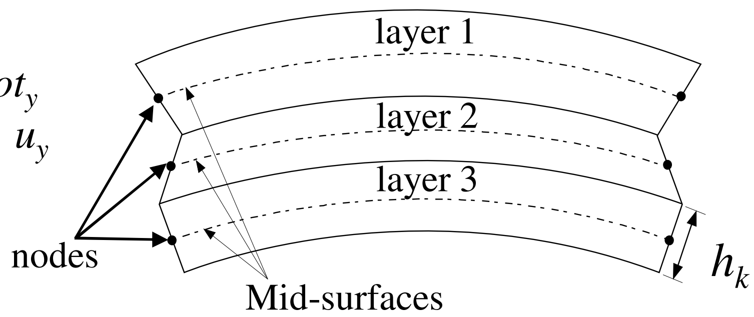
Finite Element Method

- Shell element – first order shear deformation theory based on the 3D solid degenerated element and the Reissner-Mindlin kinematical assumptions;
- 8-node shell element with 5 nodal dofs – 3 translations and 2 rotations;
- "Layer-wise" theory to model laminated structures ➡ more accurate results.
- Composite layers - fibers are oriented to improve the performance of the structure

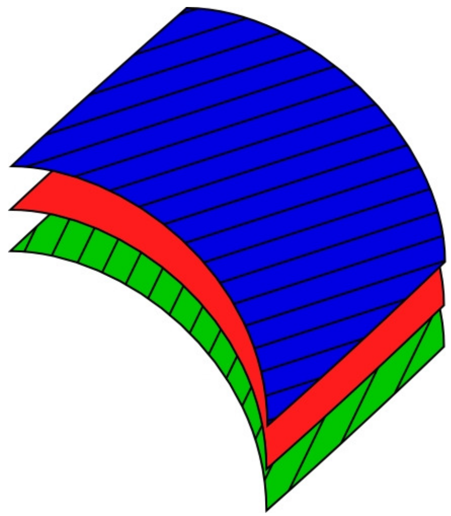
(Reddy, 2002; Ahmad et al, 1970; Kögl & Bucalem, 2005)



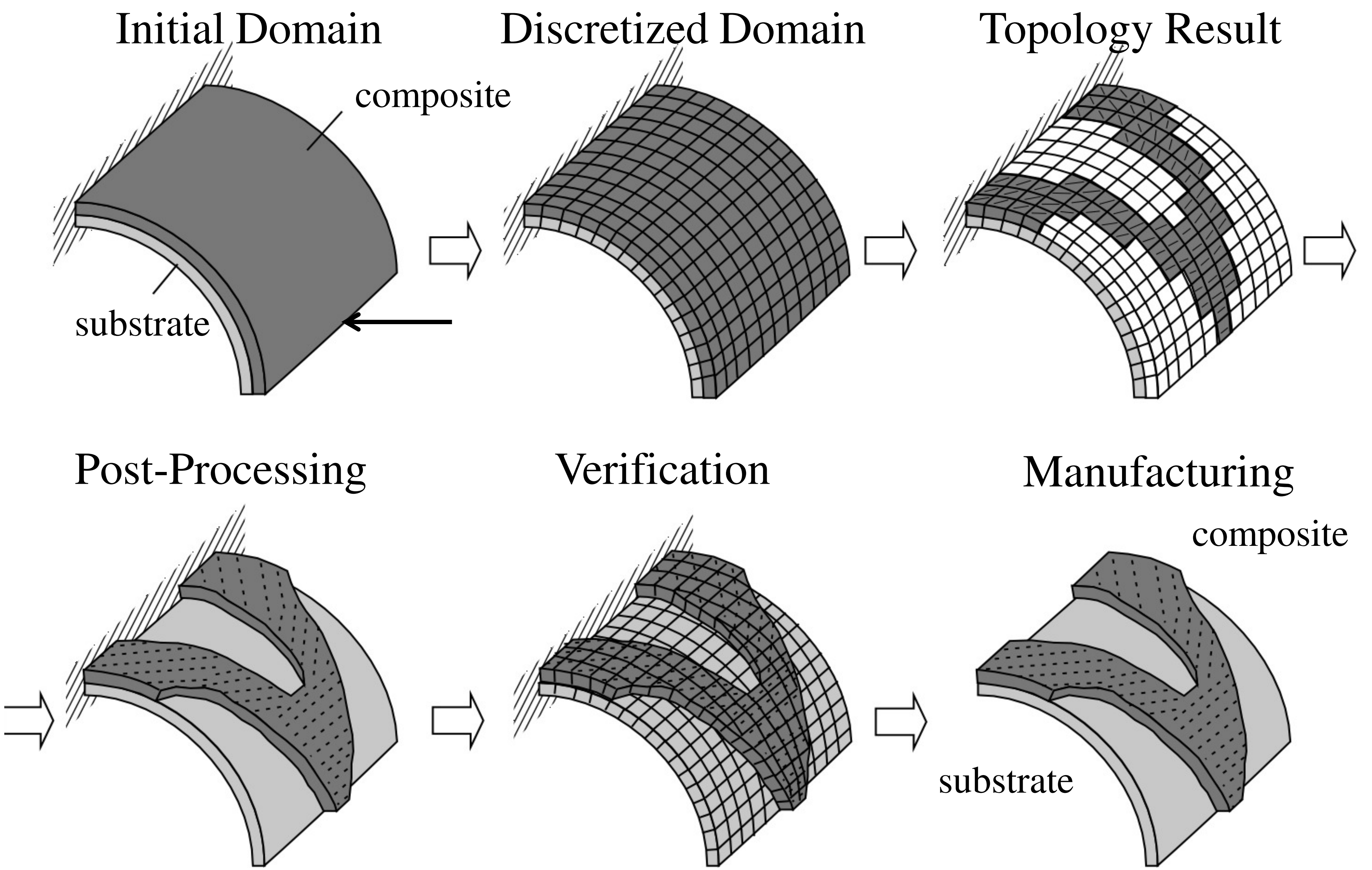
Layer-wise displacement field



Multilayer Composite Shell Structure



Topology Optimization Method

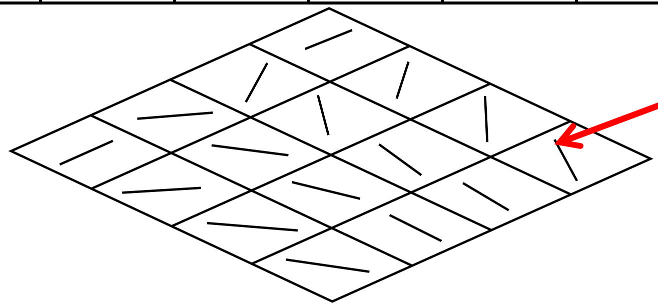


Material Model

Material distribution model	Fiber orientation model
SIMP (Simple Isotropic Material with Penalization) $\mathbf{C}_e = \gamma_e^{p_c} \mathbf{C}_0$ (Rozvany, 2001)	**DMO** (Discrete Material Optimization) $\mathbf{C} = \sum_{i_c=1}^{n^c} w_{i_c} \mathbf{C}_{i_c} = w_1 \mathbf{C}_1 + w_2 \mathbf{C}_2 + \cdots + w_{n^c} \mathbf{C}_{n^c}$ $w_{i_c} = \frac{\hat{w}_{i_c}}{\sum_{j=1}^{n^c} \hat{w}_j}, \quad \text{where} \quad \hat{w}_{i_c} = \left(\theta_{i_c}^e\right)^{p_\theta} \prod_{l=1, l \neq 1}^{n^c} \left(1 - \left(\theta_{i_c}^e\right)^{p_\theta}\right)$ (Lund, 2009)

Material Candidates – 13 angles

0º	-85º	-75º	-60º	-45º	-30º	-15º	15º	30º	45º	60º	75º	85º



13 orientation variables θ_i^e at each element

Numerical Implementation

Nodal Pseudo Density

⬡ Pseudo Density γ_k

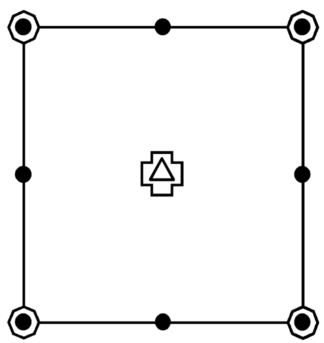
$$\gamma_e = f\left(\gamma_k\right)$$

Nodal Variable

⬡ Topology Variable d_k

Element Variables

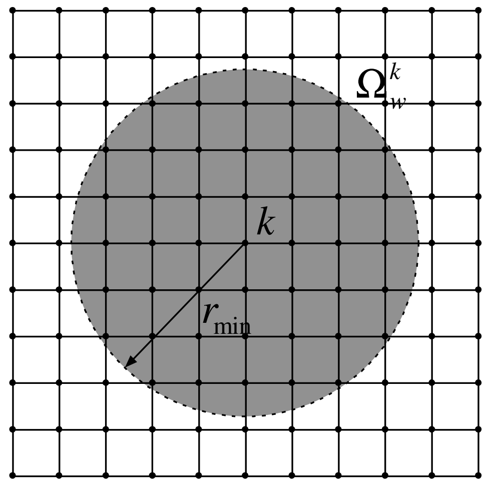
△ Orientation Variable $\theta_{i_c}^{e}$



● nodes

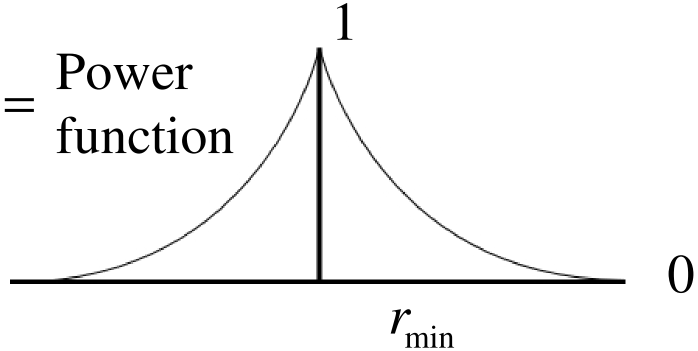
Projection technique

(Guest et al., 2004)



$$\gamma_k = f\left(d_i, \overline{w}_i\right) \qquad \tilde{\theta}_{i_c}^{e} = f\left(\theta_{i_c}^{e}, \overline{w}_i\right)$$

$\overline{w}_i =$ Power function



(Almeida et al., 2010)

Problem Formulation

Minimize *P*-norm of Tsai-Wu failure criteria at composite layers

So that →

Internal Pressure can be increased

P-norm

$$\Im = \left(\sum TW_i^{\,p}\right)^{1/p}$$ i = Gauss points at each element

Tsai - Wu

$$TW_i = Y_1\sigma_{11_i} + Y_2\sigma_{22_i} + Y_1\sigma_{11_i}^2 + $$
$$+ Y_2\sigma_{22_i}^2 + 2Y_{12}\sigma_{11_i}\sigma_{22_i} + Y_{66}\tau_{12_i}^2 \le 1$$

$$Y_1 = \frac{1}{F_{11}^T} - \frac{1}{F_{11}^C} \; ; \; Y_2 = \frac{1}{F_{22}^T} - \frac{1}{F_{22}^C} \; ; \; Y_{11} = \frac{1}{F_{11}^T F_{11}^C}$$

$$Y_{22} = \frac{1}{F_{22}^T F_{22}^C} \; ; \; Y_{66} = \frac{1}{F_{66}^2} \; ; \; Y_{12} = -\frac{\sqrt{Y_1 Y_2}}{2}$$

F_{11}^T, F_{22}^T Traction failure stresses along directions 1 and 2

F_{11}^C, F_{22}^C Compression failure stresses along directions 1 and 2

F_{66}^2 Shear failure stress

$$\underset{d_i \;\; \theta_i^e}{\text{Minimize}} \quad \Im$$

Subject to: $\int_{Volume} \gamma_e \, dV \le V_{frac}$

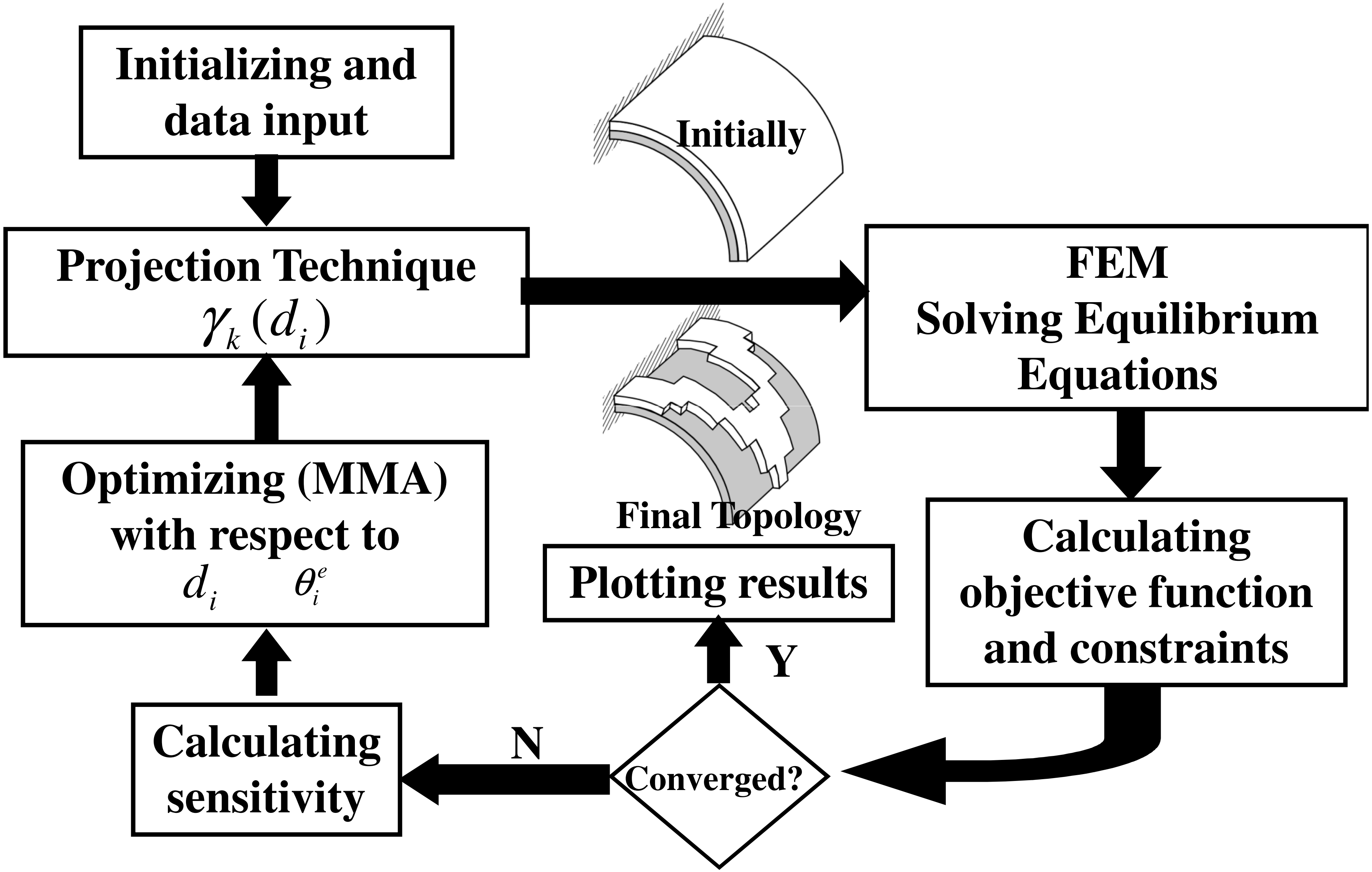
$$0 < d_i \le 1$$

$$0 \le \theta_i^e \le 1$$

Solved using MMA (Svanberg,1987)

(Pereira et al. 2003, Le et al. 2010)

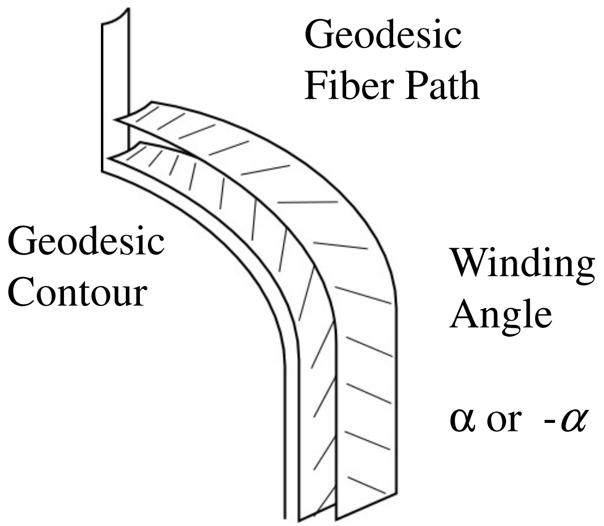
Topology Optimization Flowchart



Problem Formulation – Two Approaches

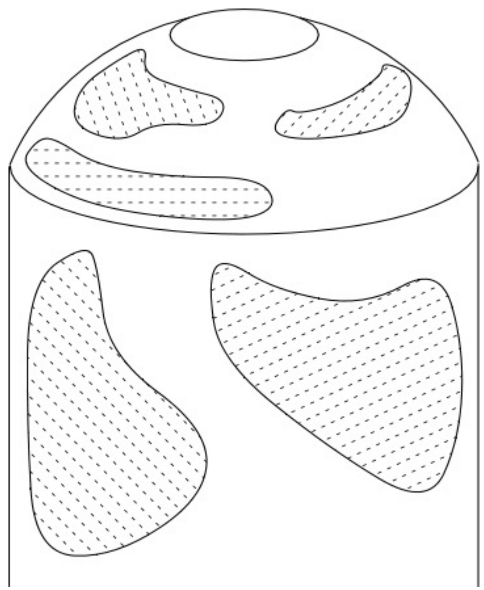
Case 1 – Winding

- Winding Angle Optimization;
- No material is removed ;
- Geodesic Contour is updated to fit the geodesic fiber path according to winding angle ($R \sin\alpha = cte.$);
- Winding angle of alternated layers are equal to α or $-\alpha$;
- Cyclic Symmetry is considered for FEM model.



Case 2 – Fiber placement

- Topology and fiber angle optimization (simultaneously);
- Vessel contour does not change;
- Resultant angles can be different for each finite element;
- Entire FEM model considered (more generic).

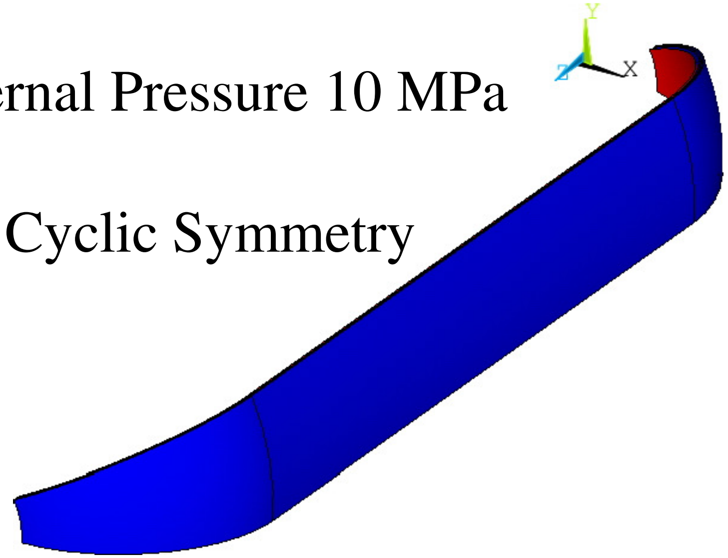


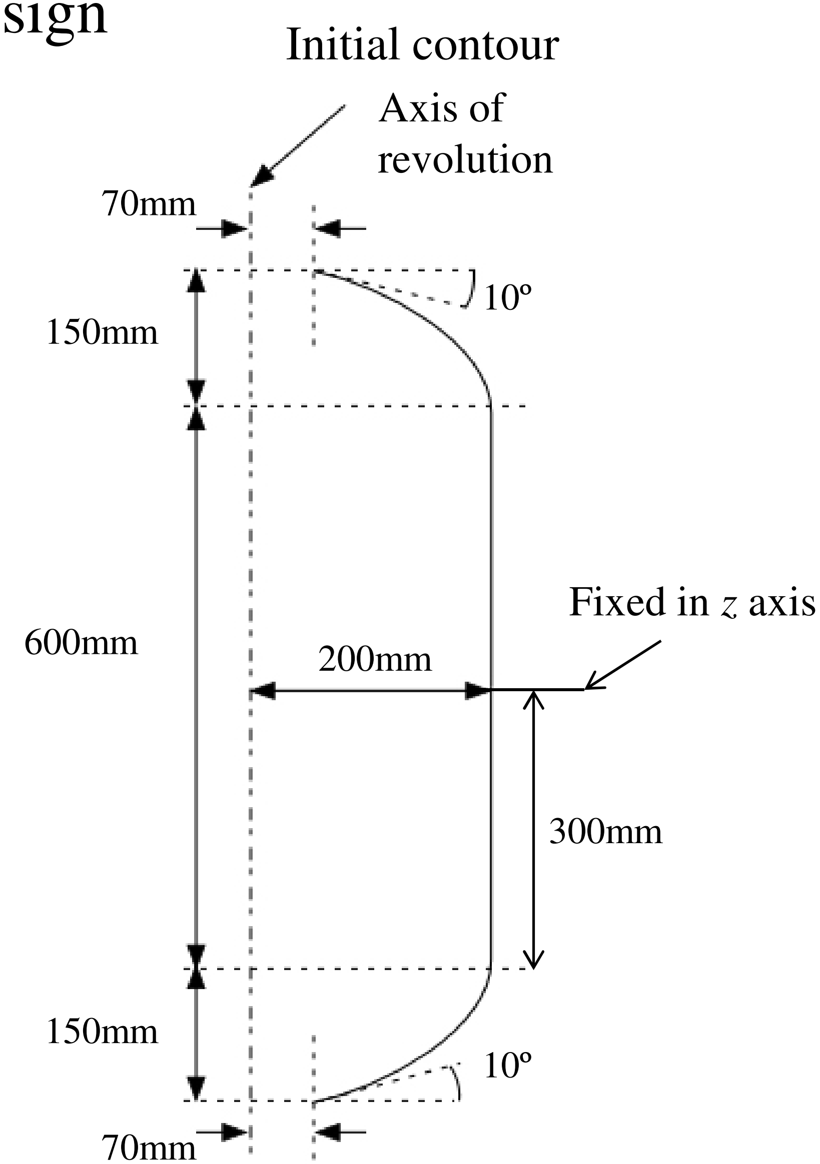
Problem Design – Case 1

Winding-type Design

Internal Pressure 10 MPa

Cyclic Symmetry





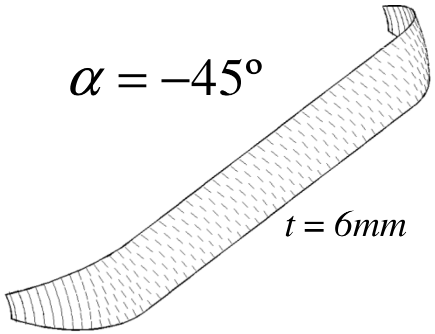
- 'inner' layer – Aluminum – red – $t = 4mm$
- 'other' layers – Glass Fiber – blue – $t = 6mm$ (sum of all layers thickness is kept constant)

3 examples explored
- 1 composite layer
- 2 composite layers
- 3 composite layers

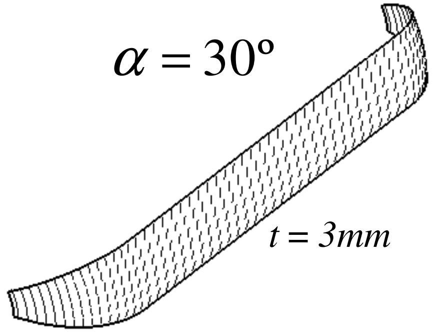
Results – Case 1

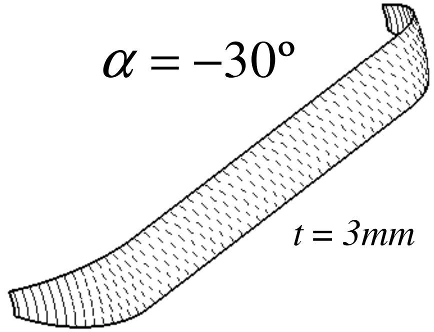
Nº composite layers	Optimal winding angle (discrete)	Maximum Tsai Wu value for 10 MPa	Maximum optimized internal pressure
1 (not optimized)	0º (hoop direction)	0.76	11.9 MPa
1	-45º	0.11	22.8 MPa
2	30º	0.21	17.9 MPa
3	30º	0.12	22.5 MPa

1 composite layer

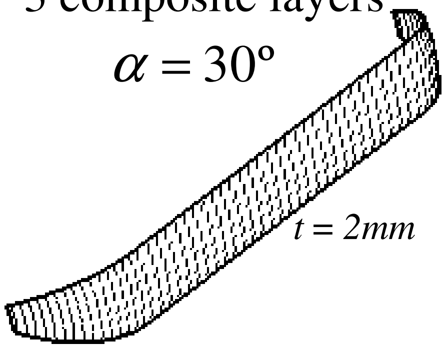


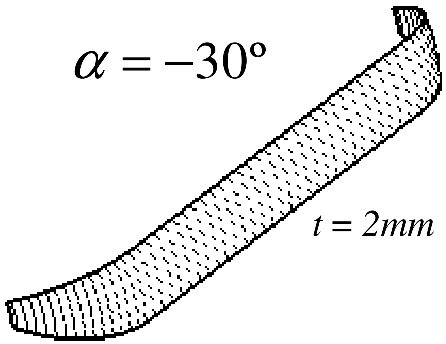
2 composite layers

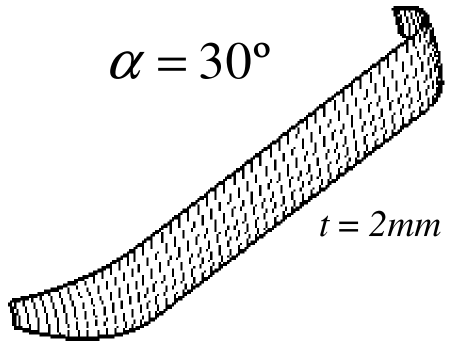




3 composite layers

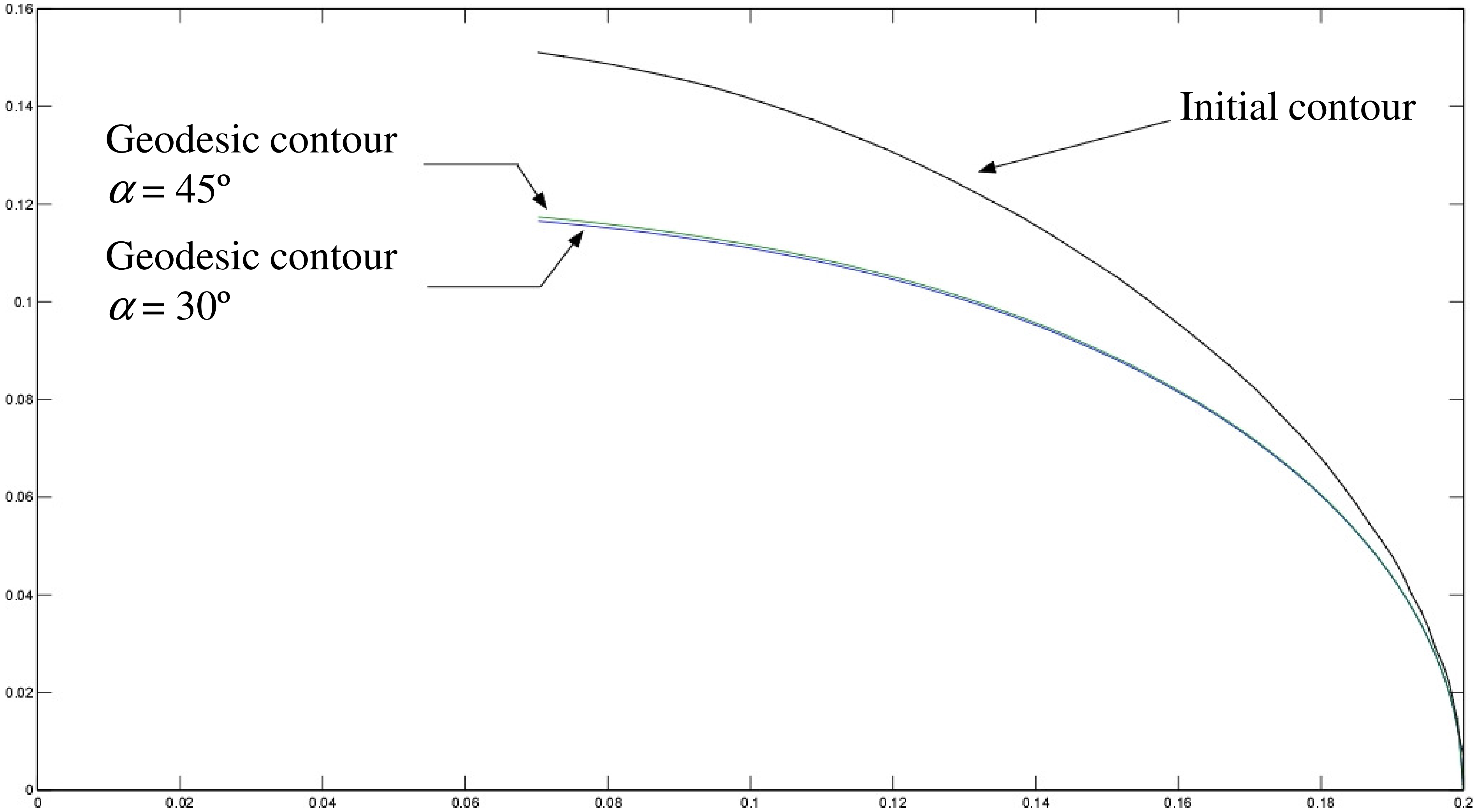






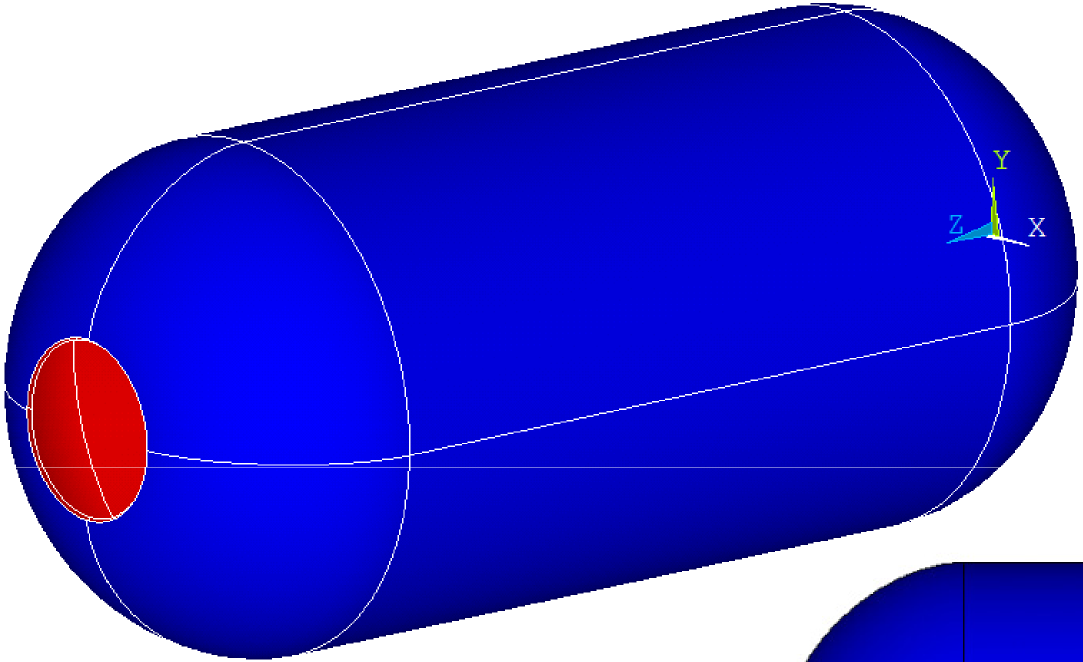
Results – Case 1

Dome Contour



Problem Design – Case 2

Fiber Placement-type Design



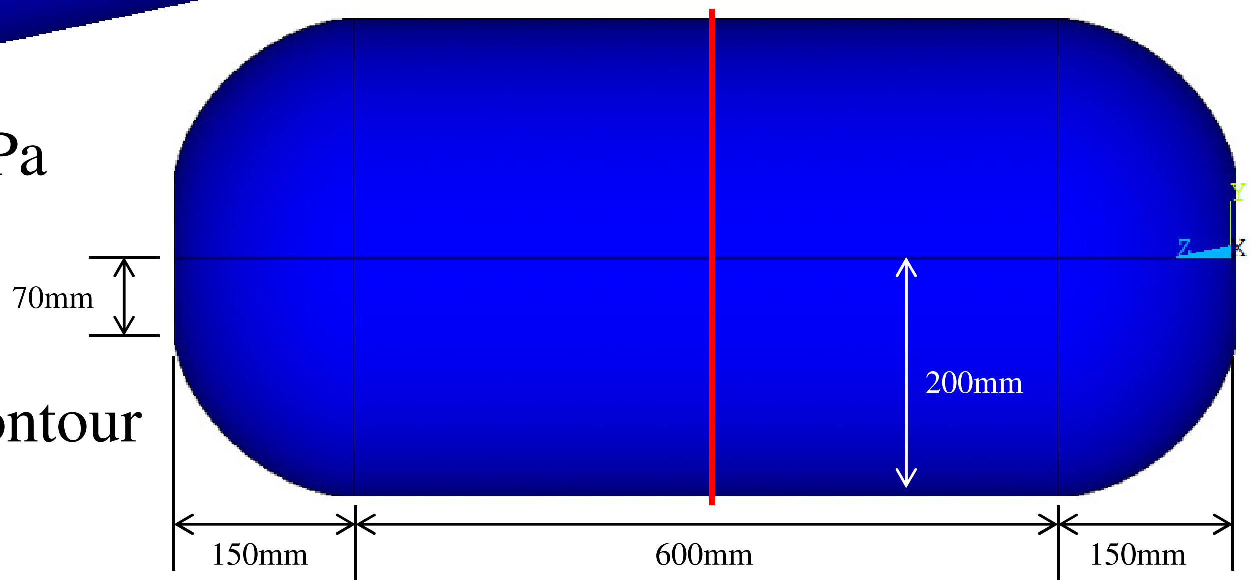
2 Layers

- ‘inner’ layer – not optimized
  Aluminum – red – $t = 4mm$
- ‘outer’ layer – design domain
  Glass Fiber – blue – $t = 2mm$
  Initial mass: 11Kg
  50% volume constraint

Internal pressure 10 MPa

Fixed in z axis

Fixed Contour

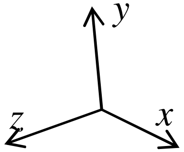


Topology Result – Case 2

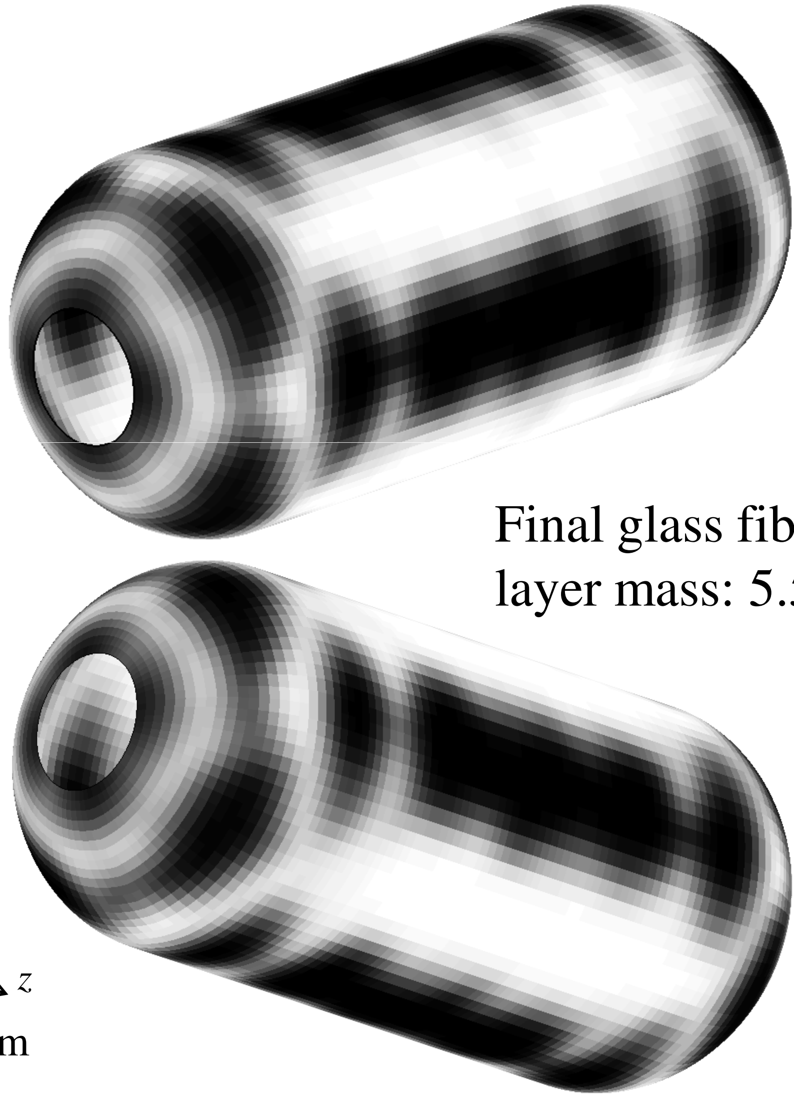
Final mesh topology

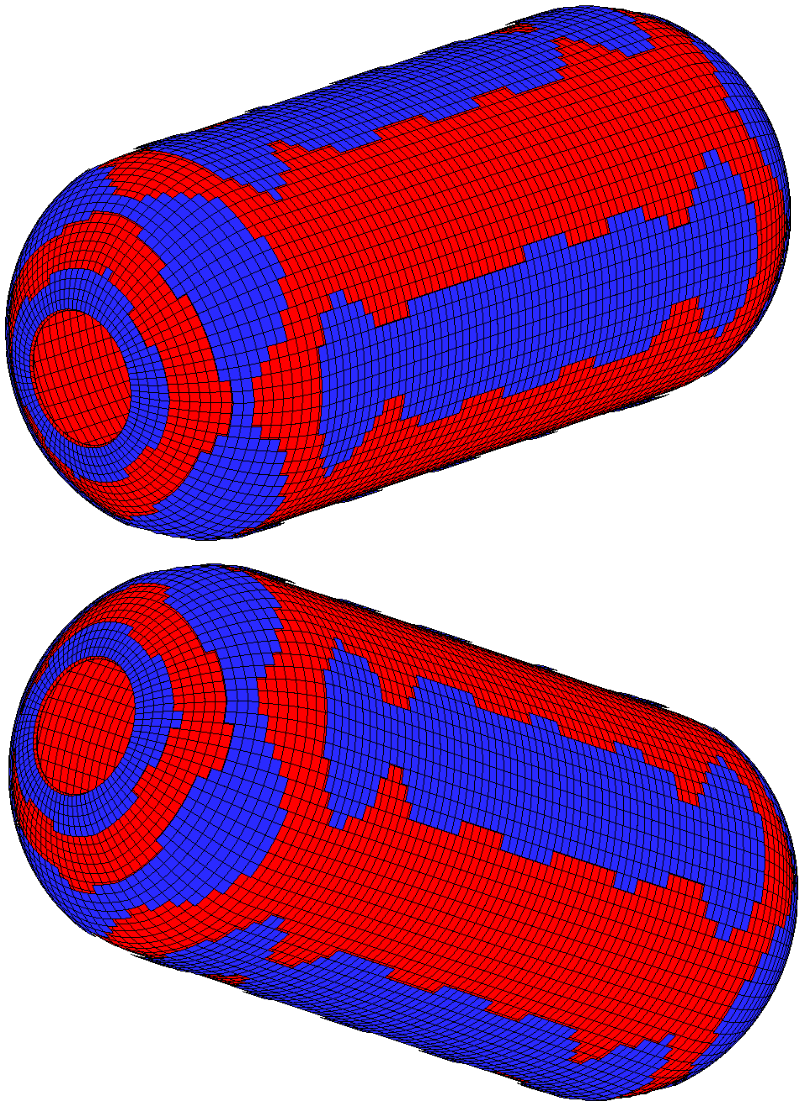
Post-Processed Topology

View 1



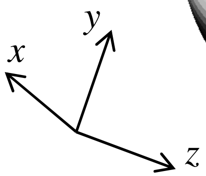
Top-front





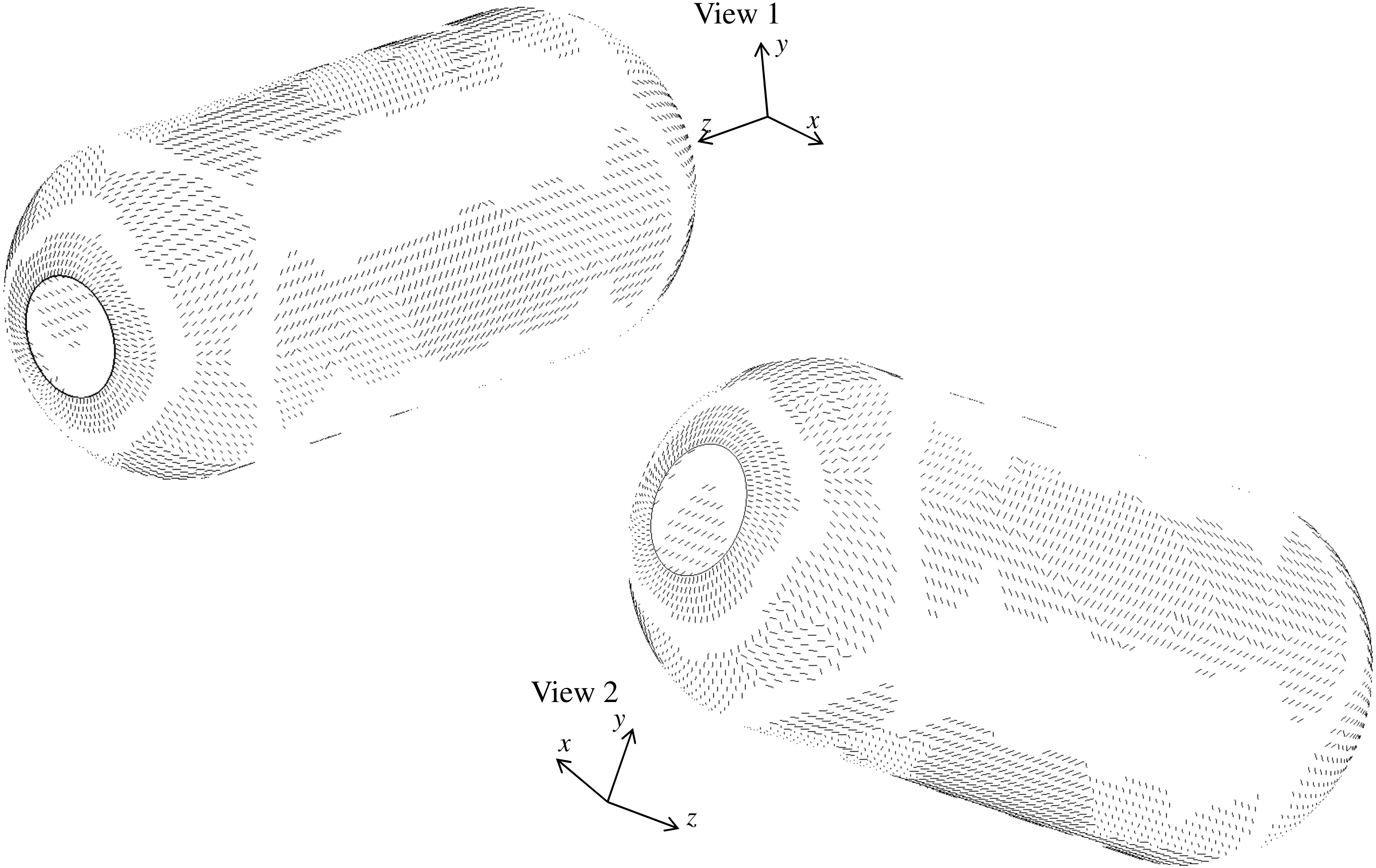
Final glass fiber layer mass: 5.5 Kg

View 2



Back-bottom

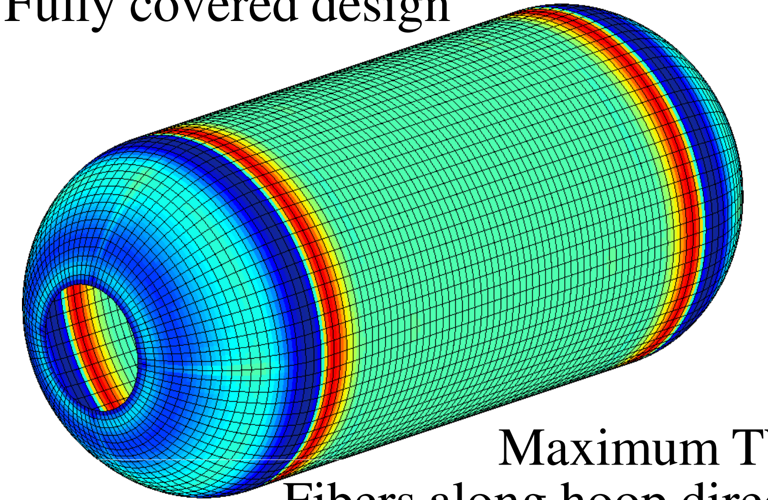
Fiber Orientation Result – Case 2



Tsai Wu criteria – Result – Case 2

Internal pressure **9.1 MPa**

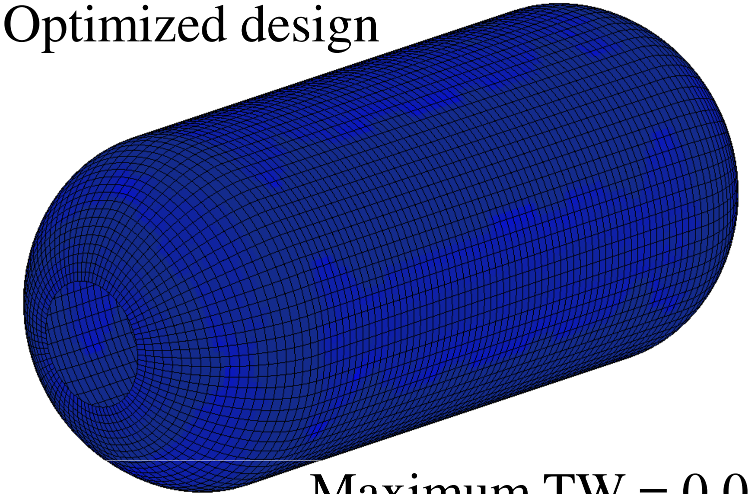
Fully covered design



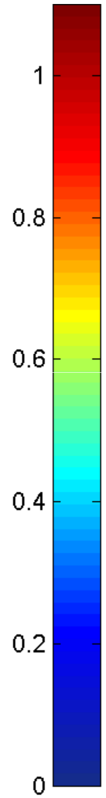
Maximum TW = 0.98

Fibers along hoop direction

Optimized design

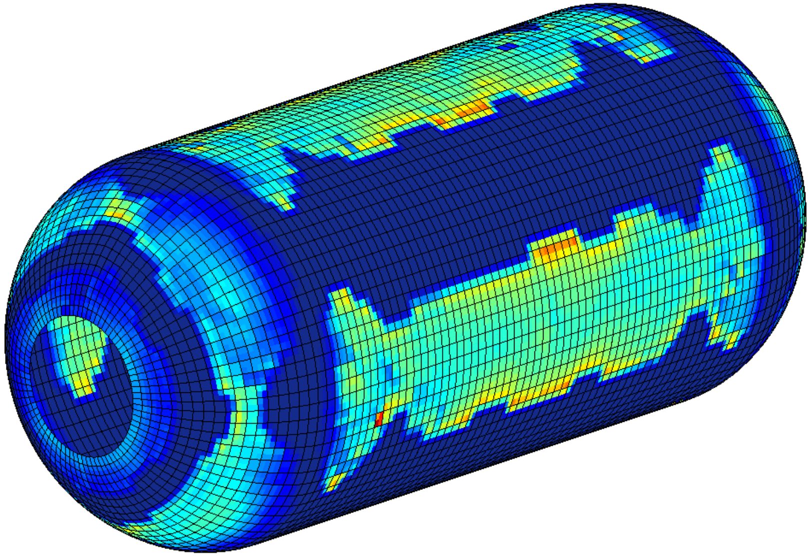


Maximum TW = 0.08



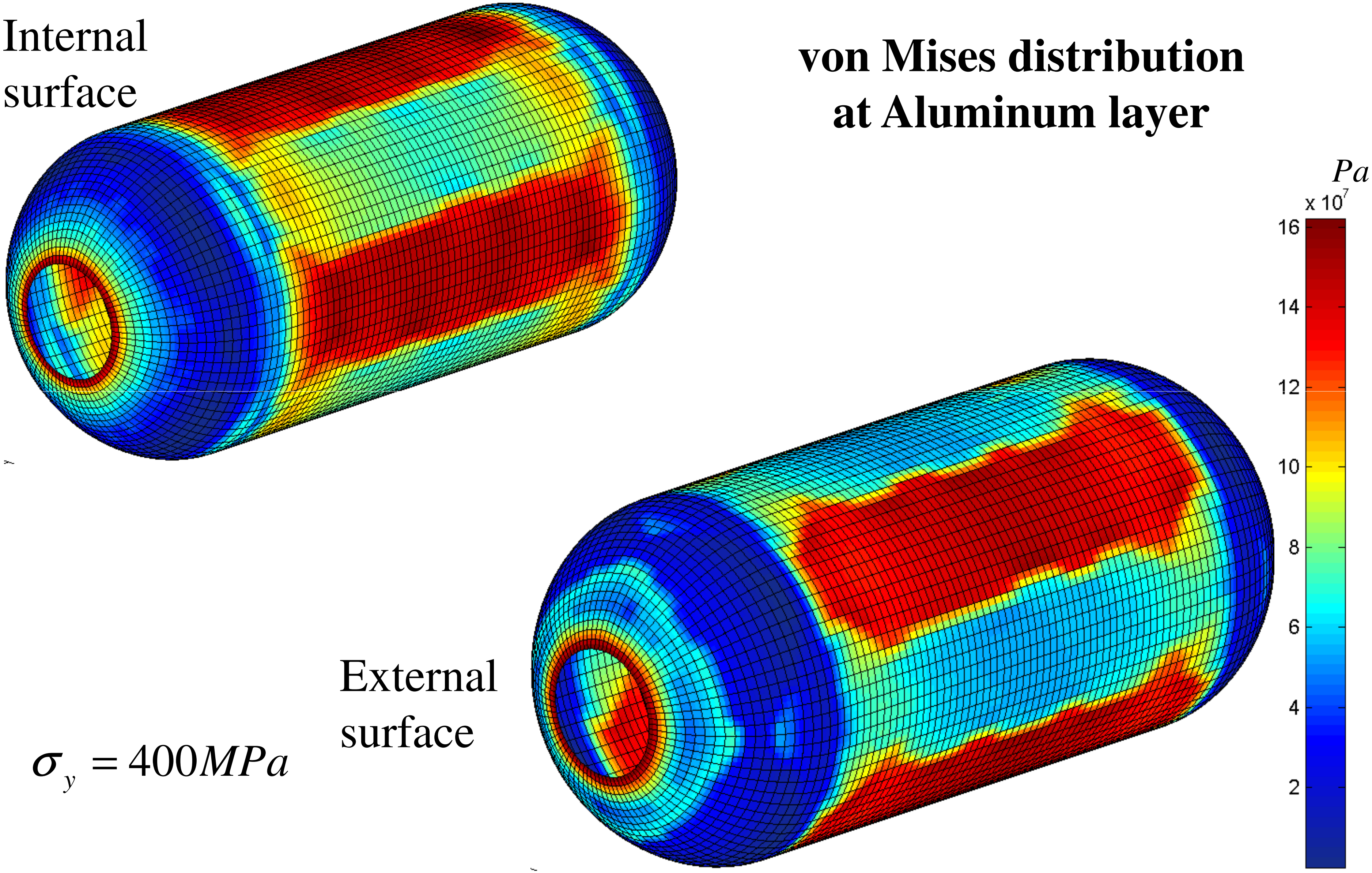
Maximum internal pressure of optimized vessel = **20 MPa**

Improvement **119,8%**



von Mises – Result – Case 2

von Mises distribution at Aluminum layer



$\sigma_y = 400MPa$

Conclusion

- ✓ A parametric and topological optimization approaches have been implemented for winding-type and fiber placement-type vessel configurations, respectively;
- ✓ The proposed topology optimization formulation optimizes simultaneously material distribution, and fiber local orientation to minimize Tsai-Wu P-norm for CNG composite pressure vessel subjected to composite volume constraint;
- ✓ These approaches reduce the Tsai-Wu failure criteria value, allowing higher pressures inside the optimized pressure vessels, thus, increasing the quantity of storage gas and the ratio (gas mass)/(tank mass);

Future Work

- Thermal loads will be considered;
- The procedure will be extended to other types of vessels, such as, articulated vessels.

The End

Thank you

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