# Numerical Analysis and Optimal Design of Composite Thermoforming Process

**by**

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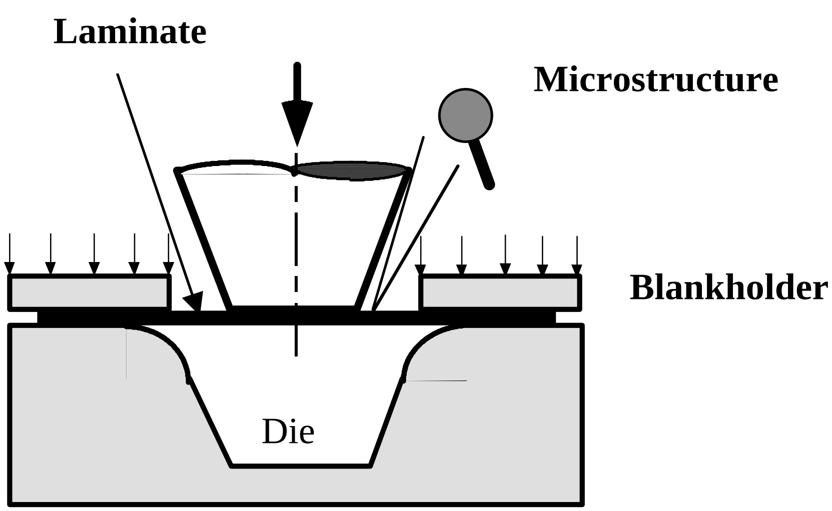
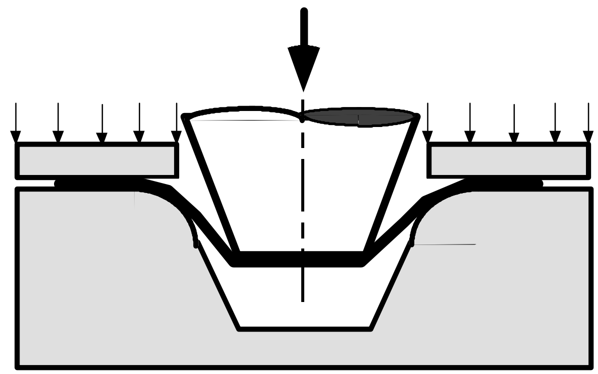
# Outline

- Introduction
- FEM Analysis of Composite Thermoforming Process
  - Rheological Characterization of Continuous fiber Composites
  - Global FEM Analysis of Thermoforming Process
  - Residual Stress Analysis
- Optimal Design of Composite Thermoforming Process
- Conclusions and Future Work

# Schematic of Thermoforming Process




**Before forming**



**After forming**

# Motivations of this research

**Deep drawing (stamping) of woven-fabric thermoplastic composites is a mass production and precision shaping technology to produce composite components.**

# Objectives of this research

- **Develop a FEM model to analyze this thermoforming process.**
- **Develop an optimization algorithm based on this FEM model to optimize this forming process.**

# Why Thermoplastic Composites?

**From the manufacturing viewpoints**

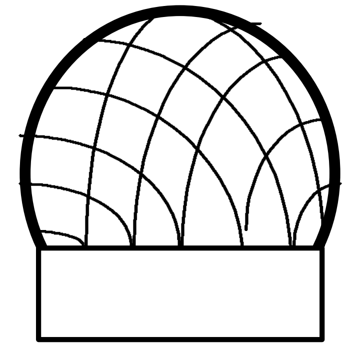
- **Thermosetting Resins**
  - **Hand layed up into structural fiber preform and impregnation after shaping**
  - **Need chemical additives to cure after shaping and very long cure cycle time**
  - **Labor intense**

- **Thermoplastic Resins**
  - **Shaping only depends on heat transfer and force without chemistry**
  - **In a preimpregnated continuous tape form**
  - **High processing rate**
  - **Drawback: higher processing viscosity and forming temperature (320~400 $^\circ$C), and higher equipment cost**

# Advantages of the composite stamping process

- Deep drawing (stamping) of woven-fabric thermoplastic composites is a mass production technology to produce composite components.
- This stamping process is also a precision shaping process.
- Woven-fabric composites possess a balanced drawability, and can avoid the excessive thinning caused by the transverse intraply shearing.

# Related work



- Kinematic approach

Potter (1979)
Robertson et al. (1981)
Van West et al. (1990)

- Under the kinematic consideration, the draping behavior of woven fabrics over 3-D spherical, conical or arbitrary surfaces was simulated by solving the intersection equations numerically.

- This approach provides a preliminary prediction of fiber buckling and final fiber orientation.

- This approach can be used as a design tool fot selecting suitable draped configurations for specific surfaces.

## • FEM Analysis

## O'Bradaigh and Pipes (1991)

## O'Bradaigh et al. (1993)

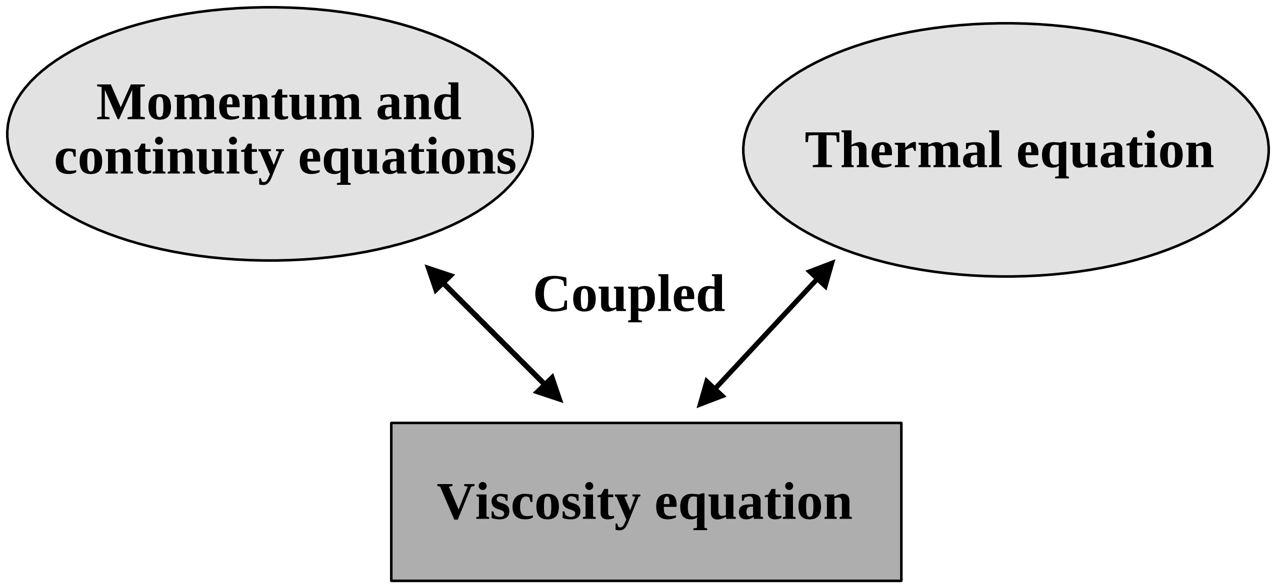
- **Diaphragm and blowing forming processes.**
- **Newtonian viscous flow formulation with the fiber inextensibility constraint**
- **Inplane prediction of macroscopic stress and strain.**
- **Isothermal forming processes.**
- **Unidirectional composite sheets.**

# Goals of this FEM Analysis

**A 3-D numerical modeling of thermoforming process on woven-fabric thermoplastic composite laminates:**

- **Characterization of the processing rheology of woven-fabric thermoplastic composite materials by the homogenization method.**
- **Coupled viscous flow and heat transfer FEM analyses for forming.**
  - **Predictions of global and local stress, temperature and fiber orientation distribution.**
- **Residual stress FEM analysis for cooling.**
  - **Predictions of macroscopic and microscopic residual stress and warpage after cooling.**

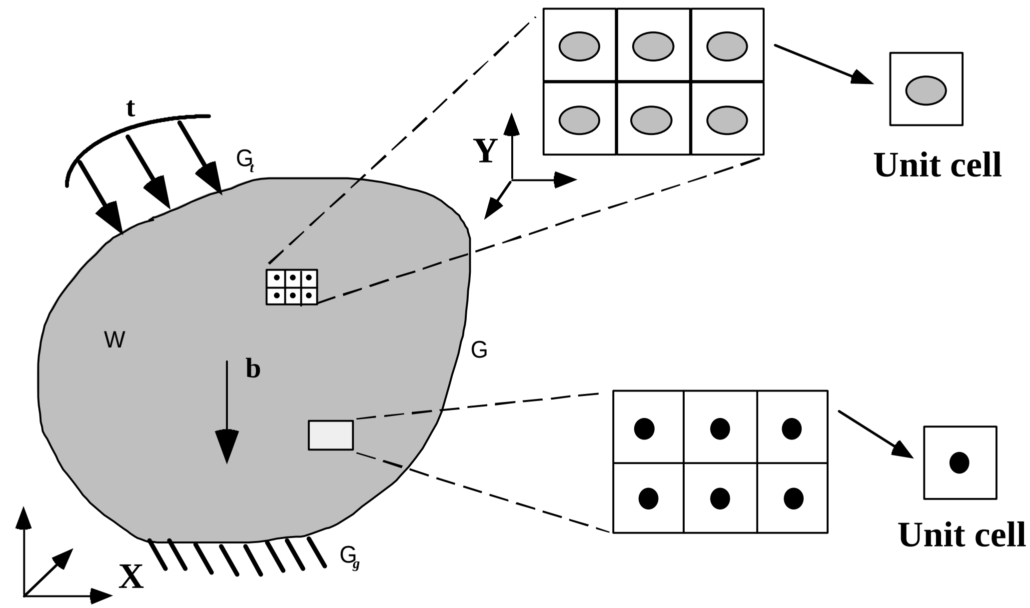
# Governing equations for thermoforming process




- Impossible to solve these equations at each microcell to obtain obtain the global response.

- Homogenization method is used to overcome this difficulty.

# Homogenization Method for Composite Materials



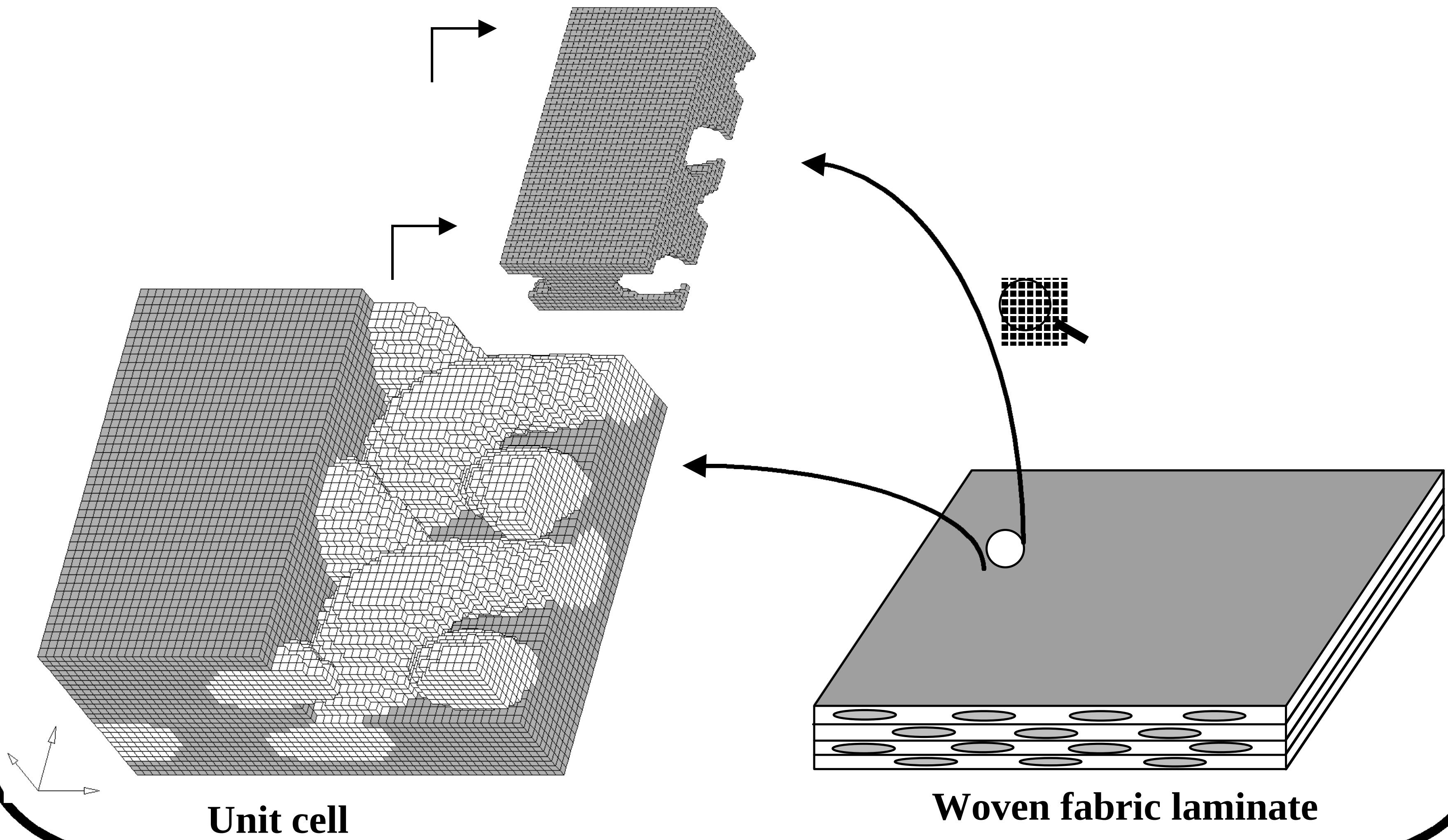

**Review**

- **Under the assumption of periodic microstructures which can be represented by unit cells.**

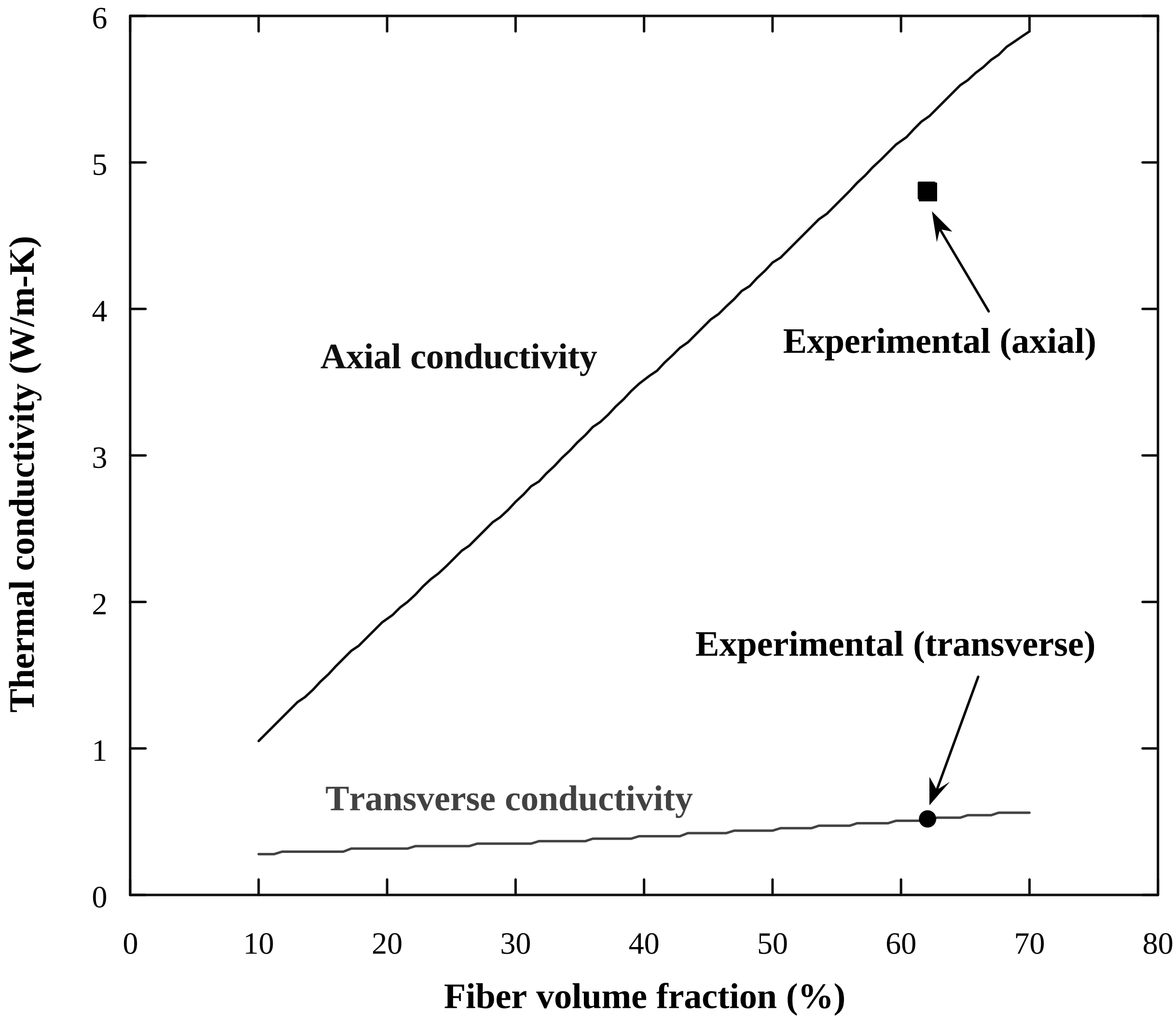
- **Using the asymptotic expansion of all variables and the average technique to determine the homogenized material properties and constitutive relations of composite materials.**

- **Capable of predicting microscopic fields of deformation mechanics through the localization process.**

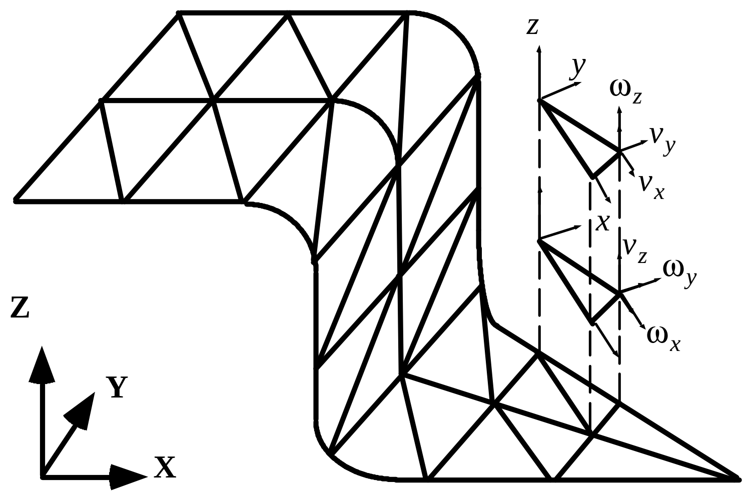
# Digitized woven-fabric unit cell



# Thermal conductivity prediction for unidirectional composites vs volume fraction



# Implementation of Global FEA




**Membrane element**

**+**

**Bending element**

**||**

**Shell element**

- **3-D sheet forming FE analysis coupled with heat transferFE analysis using 'Viscous shell with thermal analysis'.**

# Viscous shell with thermal analysis

## Viscous shell

- **Plane stress asumption-- the incompressibility constraint can be achieved by adjusting the thickness of each shell element.**
- **Large deformation process divided into a series of small time step.**
- **Complicated geometry, friction and contact considerations.**

## Coupled thermal analysis

- **Transient heat transfer FEM to solve temperature at each node.**

  **At *i-th* time step** $\underline{v}^{(i)} \rightarrow \bar{\dot{\varepsilon}}^{(i)} \Leftrightarrow \mu^{(i)} \Leftrightarrow T^{(i)}$ **are solved.**

- **At each step, solve nodal temperature and velocity iteratively until convergence.**

# Fiber Orientation Model

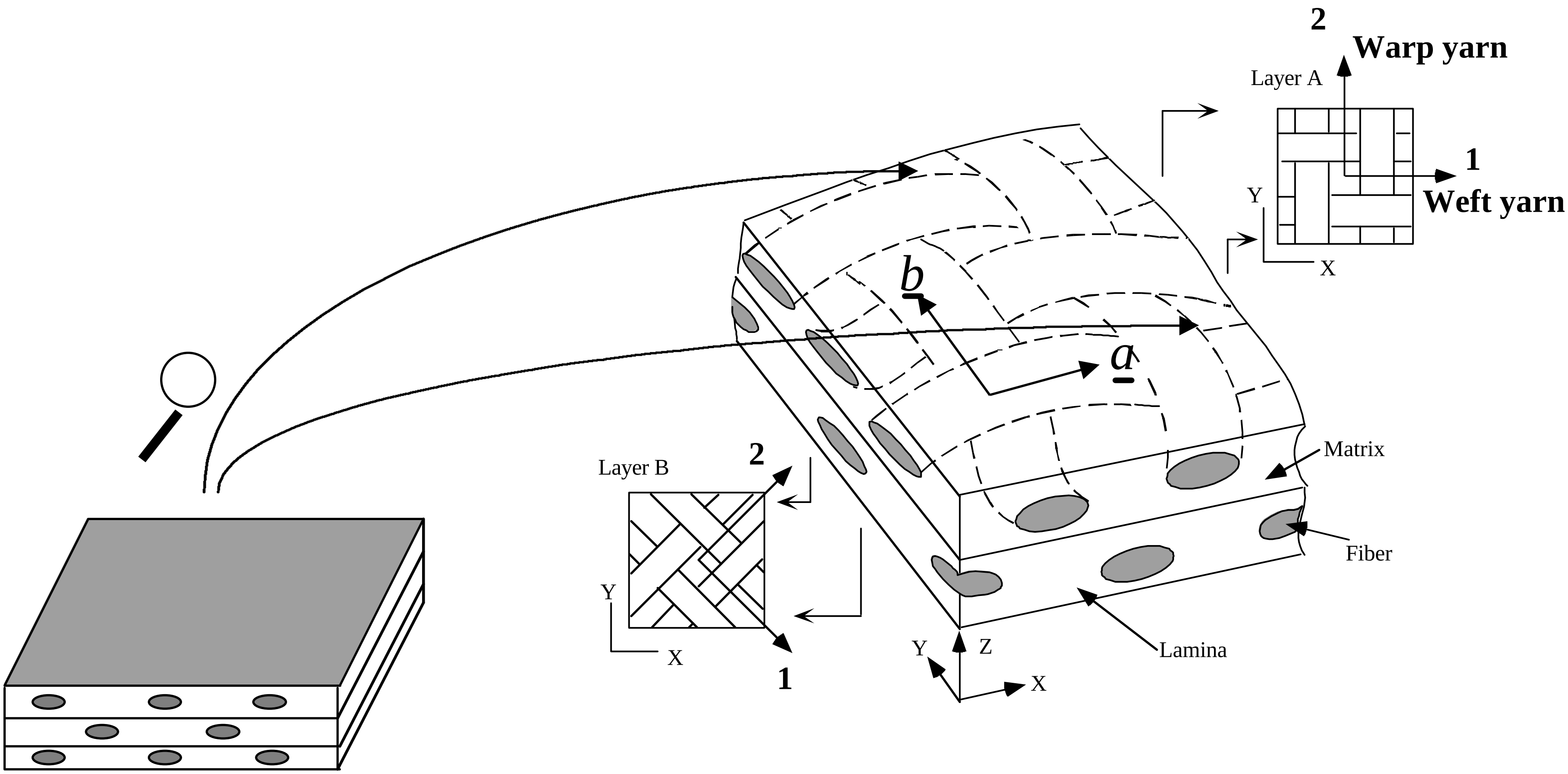
**Purposes**:

- **Update the fiber intersection angle of each global finite element by the global strain increment at every time step.**
- **Change material properties according to updated fiber orientation.**

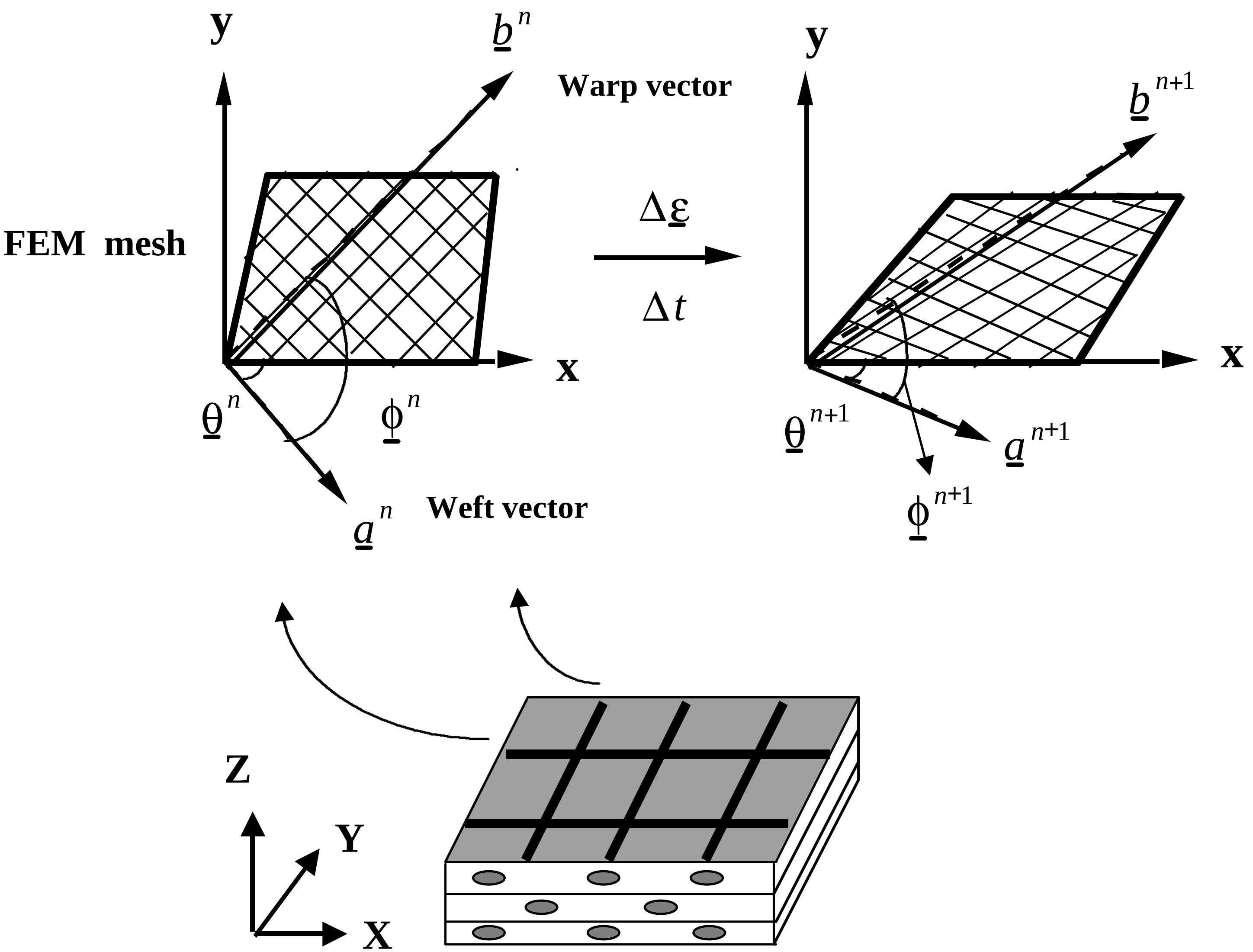
**Assumptions:**

- **The fiber orientation of all the microstructures in one global finite element is identical.**
- **The warp yarn and weft yarn of woven-fabric composites can be represented by two unit fiber vectors.**

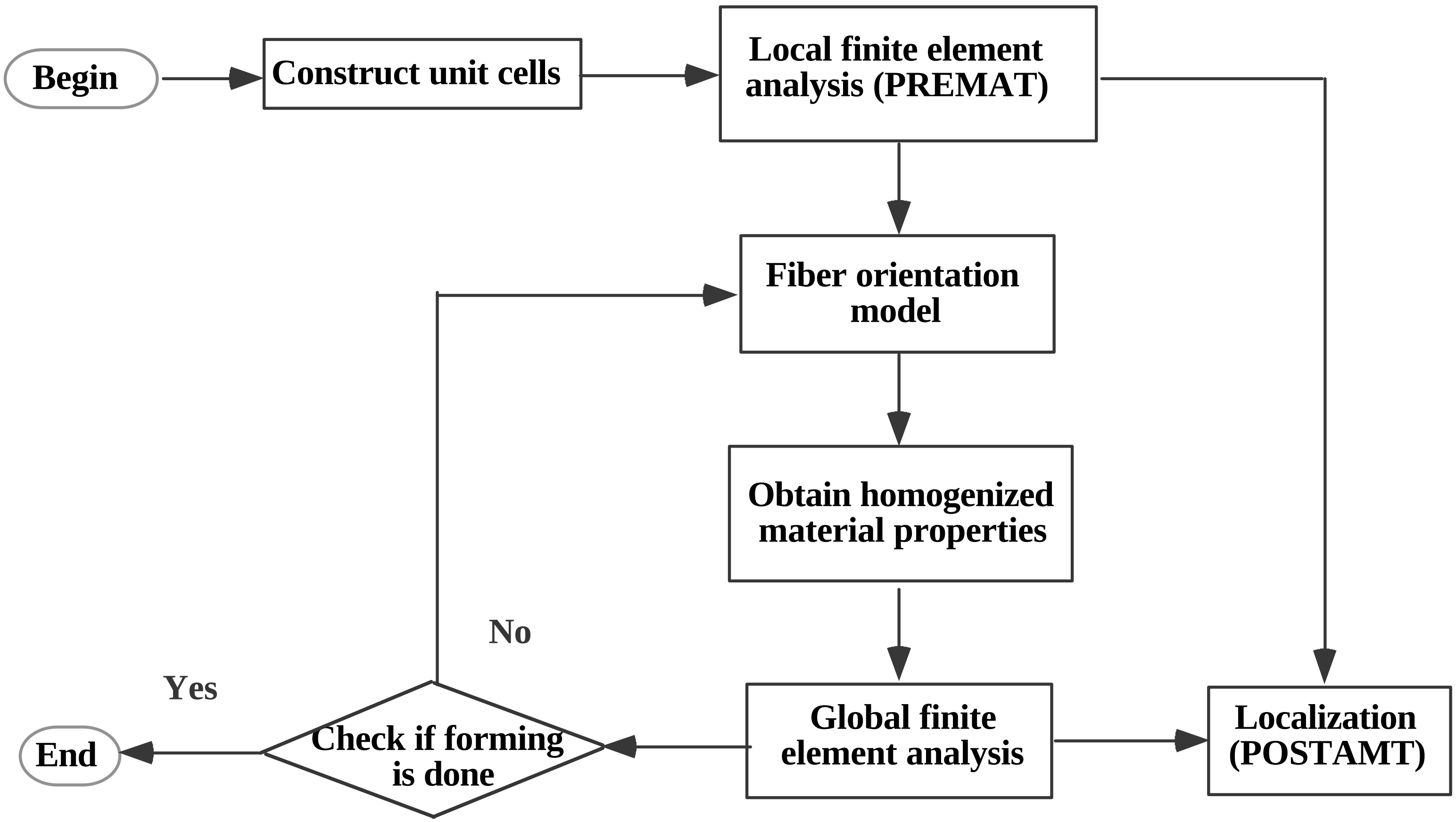
# Schematic of lamina coordinate



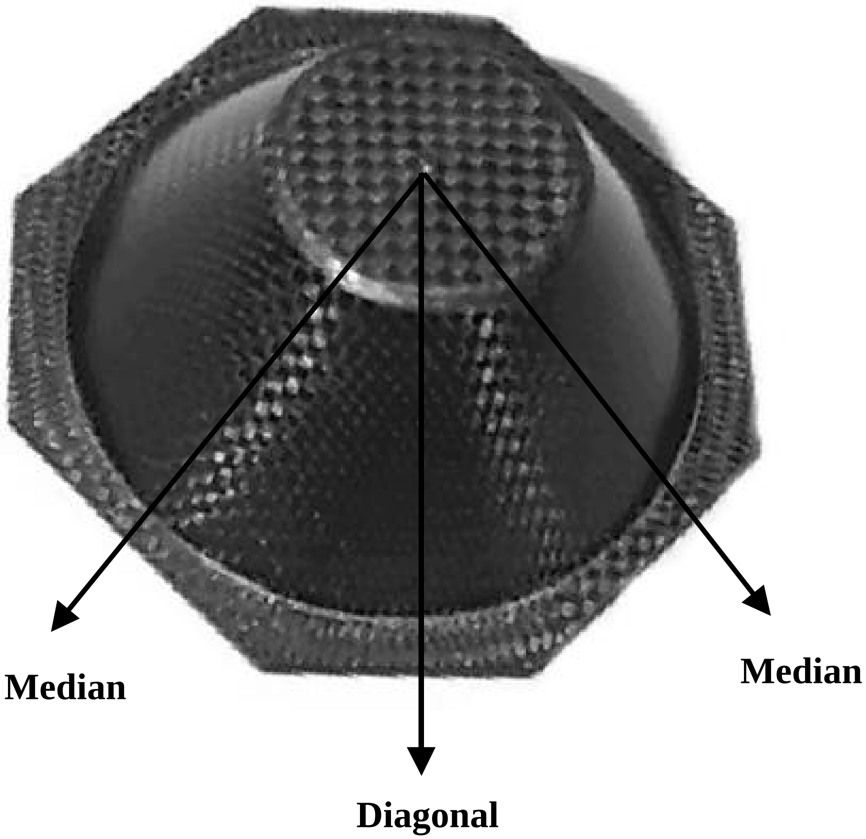
# Updating Scheme

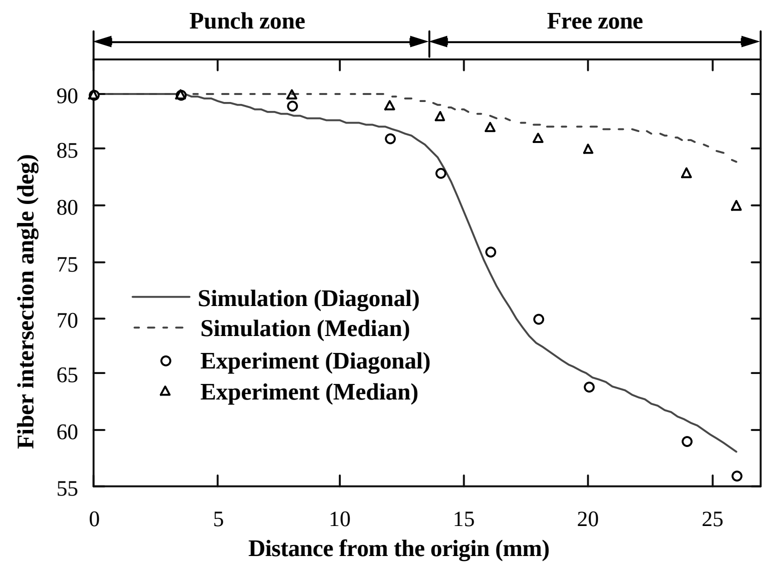


# Global-local solution scheme



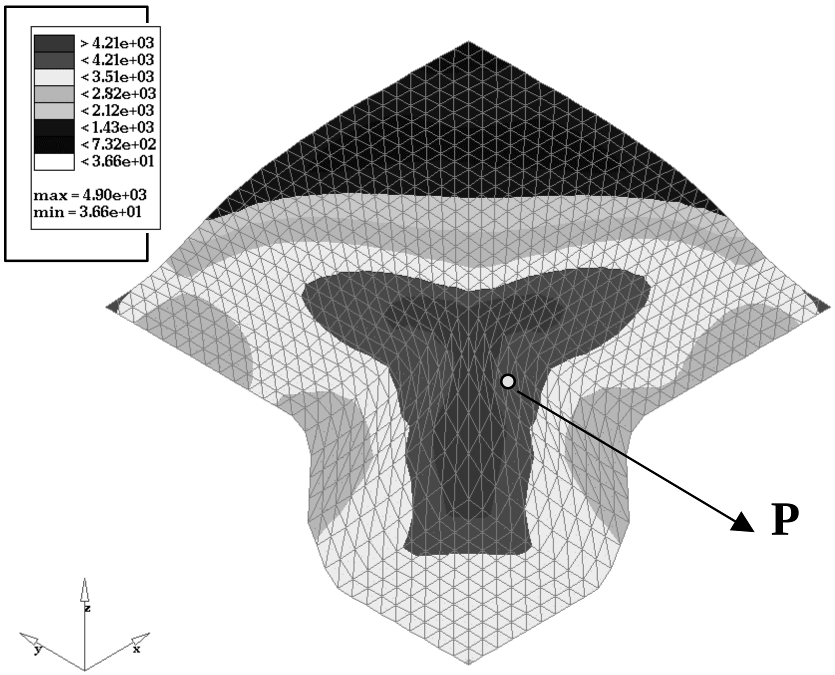
# Comparison with experiments (cylindrical cup)



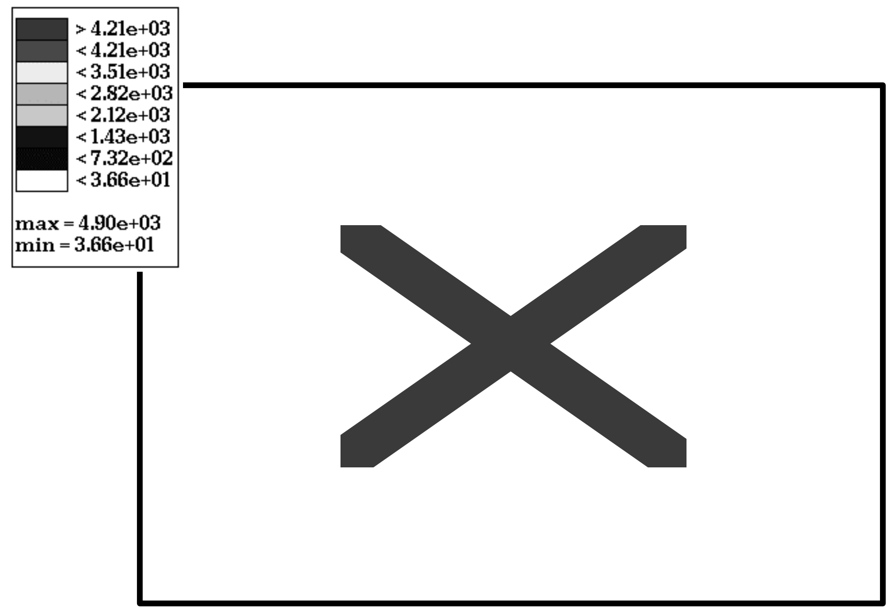



# Effective stress prediction (square box)

**Laminate**

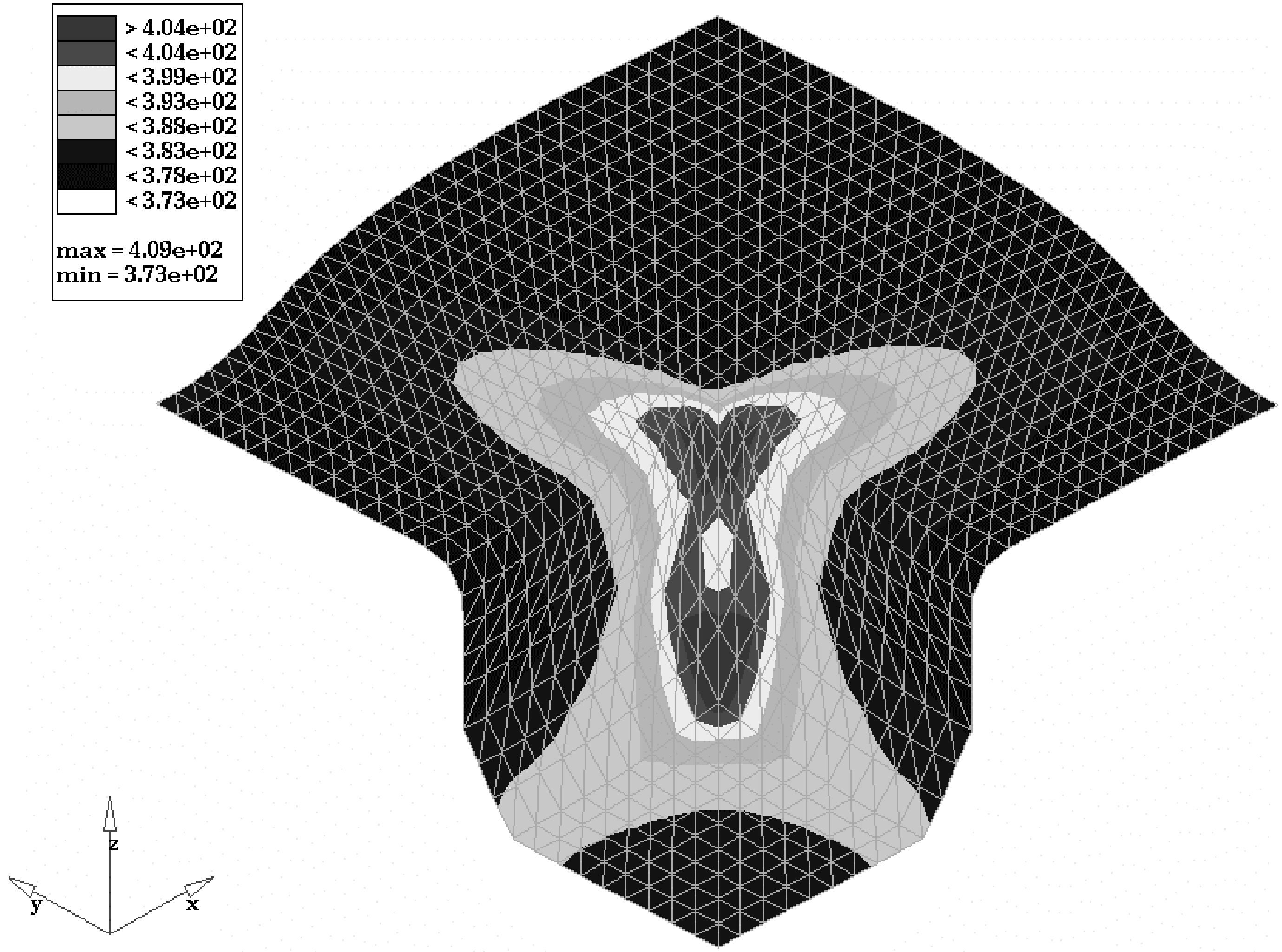



**Unit Cell**

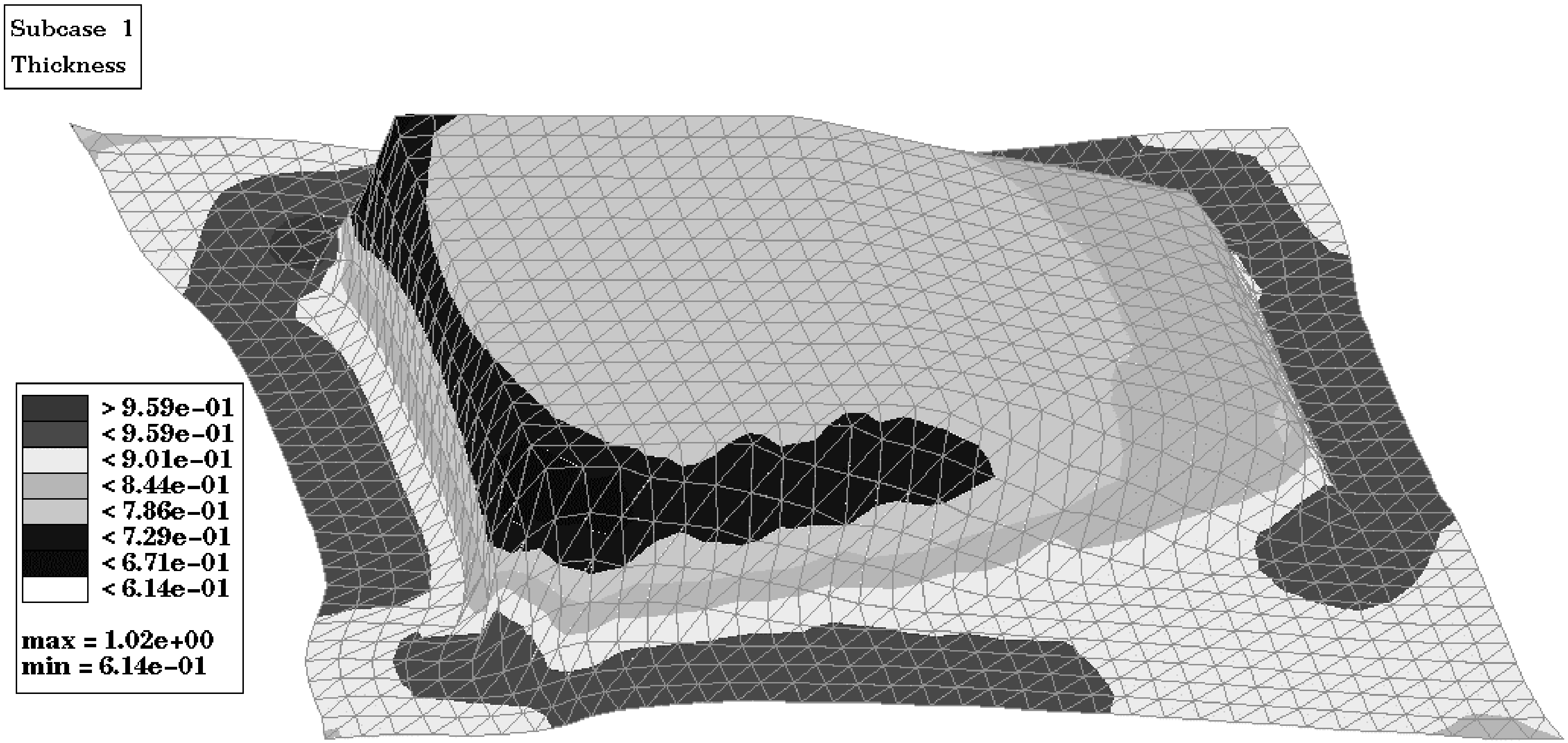



**Effective stress of laminate and unit cell at P.**

# Temperature distribution



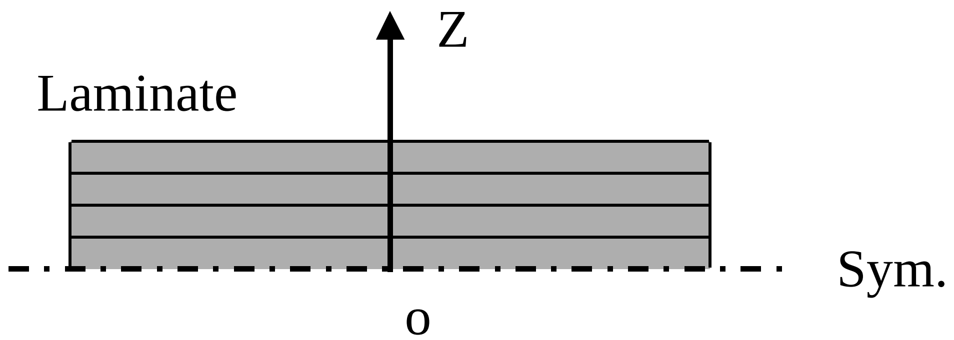
# Stamped body panel

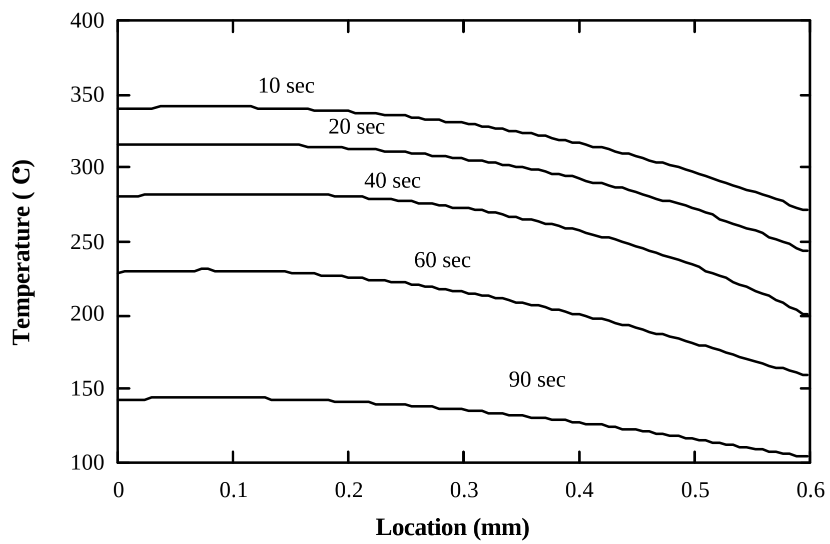


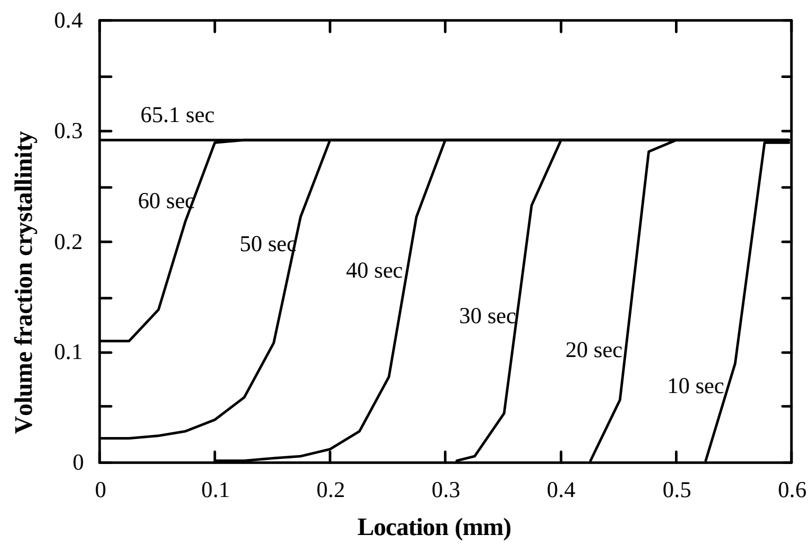
# Residual Stress Analysis

- **Three levels of residual stresses are generated during cooling**
  - **Microscopic stress: Due to CTE mismatch between matrix and fiber**
  - **Macroscopic stress: Due to stacking sequence of laminates**
  - **Global stress: Due to thermal history along laminate thickness**
- **Warpage due to the release of residual stresses after demoulding.**
- **In this study, homogenization method based on incremental elastic analysis with thermal history is adopted.**
- **Thermoelastic properties are dependent on temperature and crystallinity from the thermal history.**

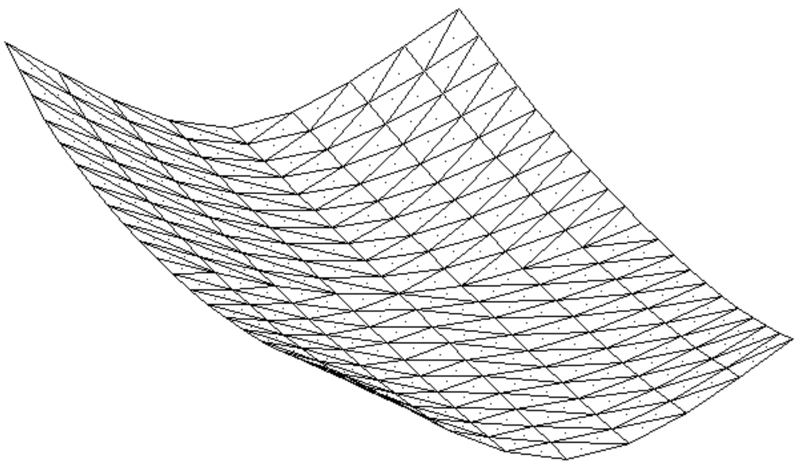
# Thermal history along thickness



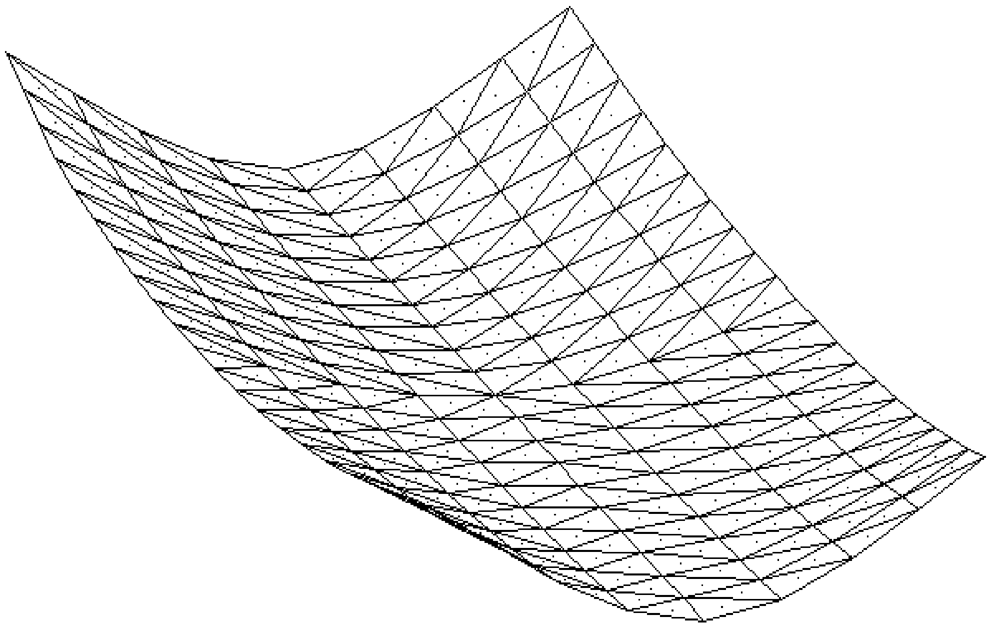



# Curvature prediction compared with experimental data



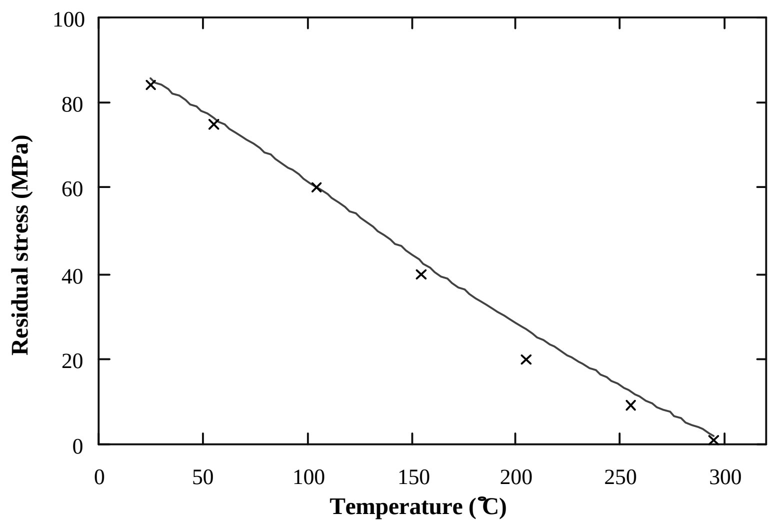
**[0/90] asymmetric laminate**



**Compared with experimental data**

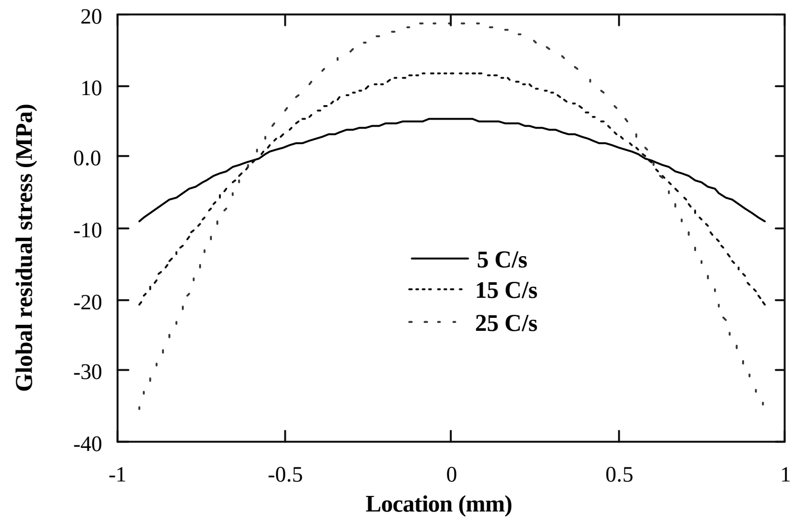
# Stress prediction compared with experimental data

## Macroscopic stress




**Macroscopic stress prediction for cross-ply laminate compared with experimental data.**

## Global stress

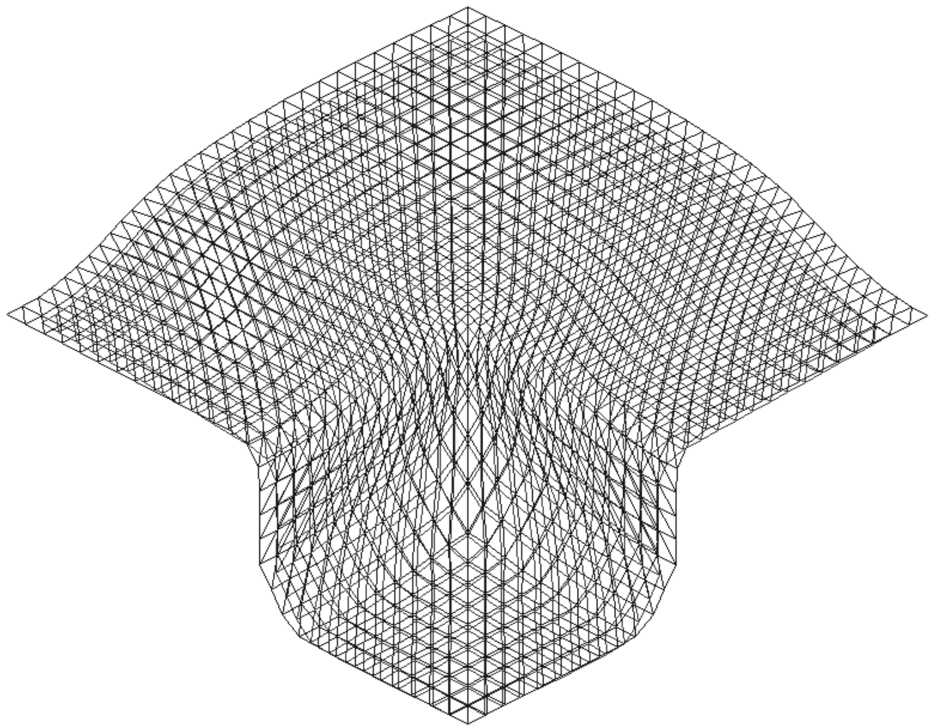



**Global stress prediction for unidirectional laminates with various cooling rates.**

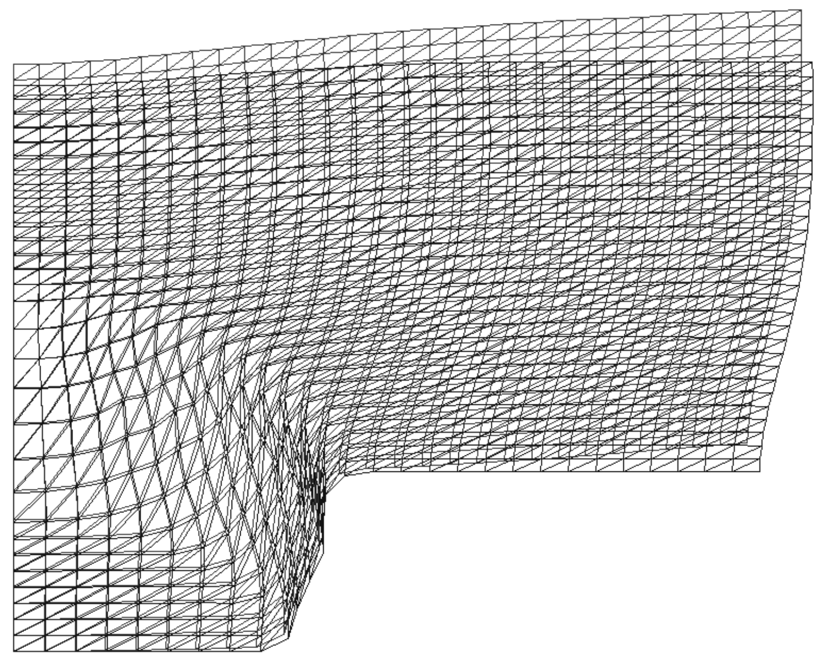
# Warped shapes of square box and cylindrical cup

**Deformed**

**Undeformed**

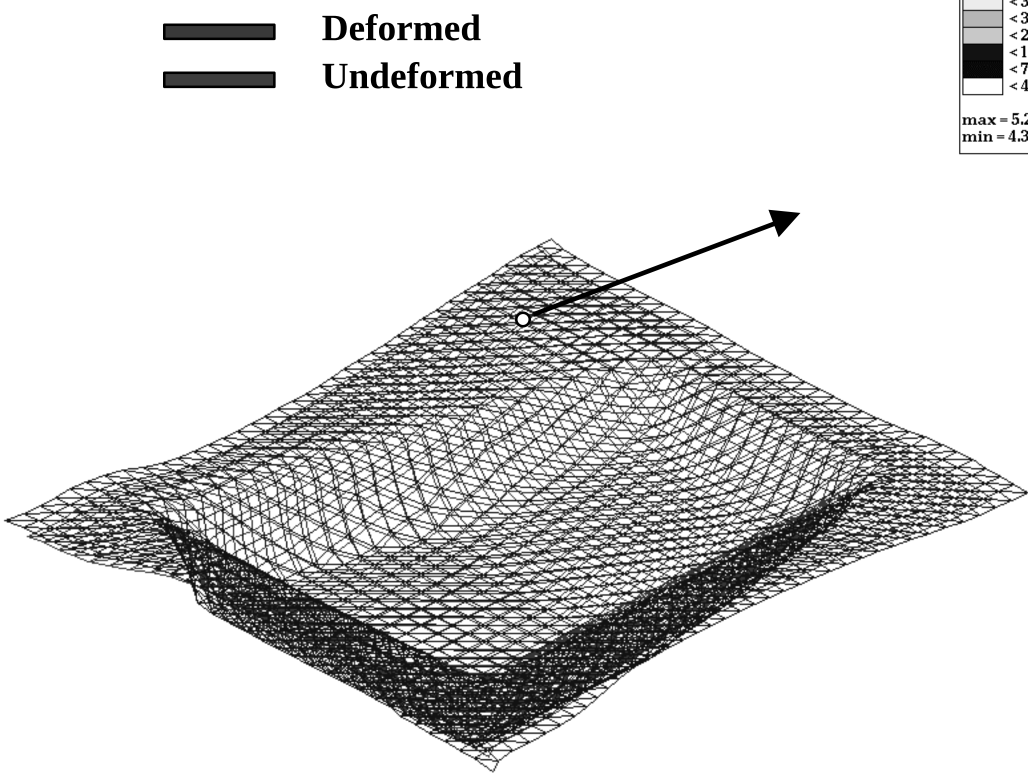


**Square box**

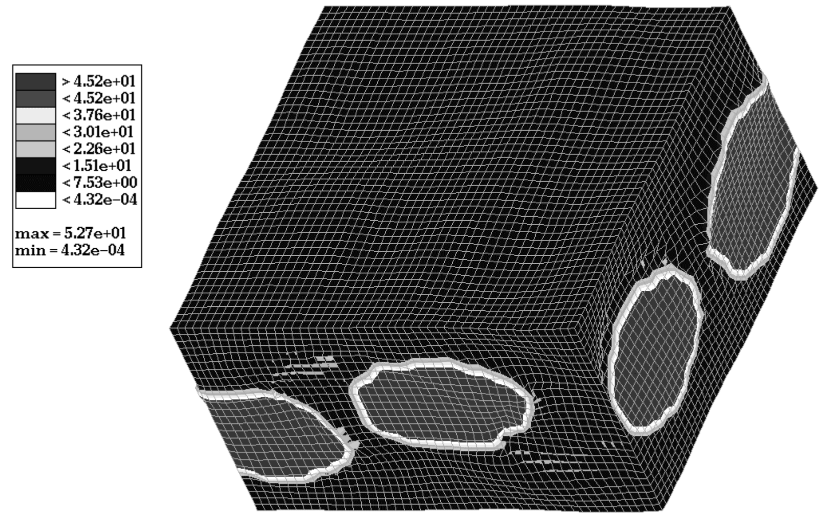


**Cylindrical cup**

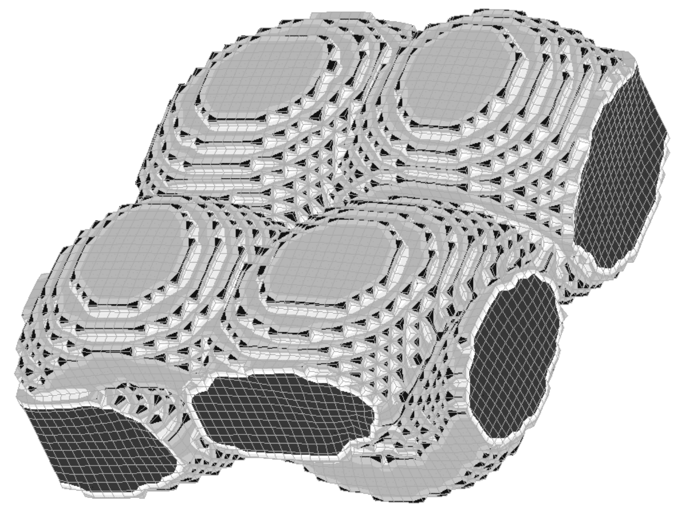
# Warped body panel with its microscopic residual stress




Laminate




Unit cell



Fiber part

# Conclusions

- **The thermoforming process of woven-fabric thermoplastic composite laminates was analyzed by the 3-D thermo-viscous flow FEM.**

- **The constitutive and energy equations of the composites forming were formulated by the Homogenization Method.**

- **The global-local analysis of the Homogenization Method enables us to examine the macro and microscopic deformation mechanics.**

- **An optimization algorithm is developed to obtain uniform distribution by adjusting preheating temperature field.**