

University of Delaware



Center for Composite Materials

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# VARTM PROCESS INCORPORATING GRAVITATIONAL EFFECTS WITH HOMOGENOUS PREFORMS

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**University of Delaware Center for Composite Materials**

## INTRODUCTION

- **Motivation:**

- ✓ Tall structures are manufactured by splitting the part in two halves, infusing each part horizontally and bonding the pieces together.
- ✓ New single-step infusion process reduces costs and achieve the goal of unified structures.

- **Application examples:**

- ✓ Construction of large-scale hulls
- ✓ Rehabilitation of bridge piers



- **Objectives:**

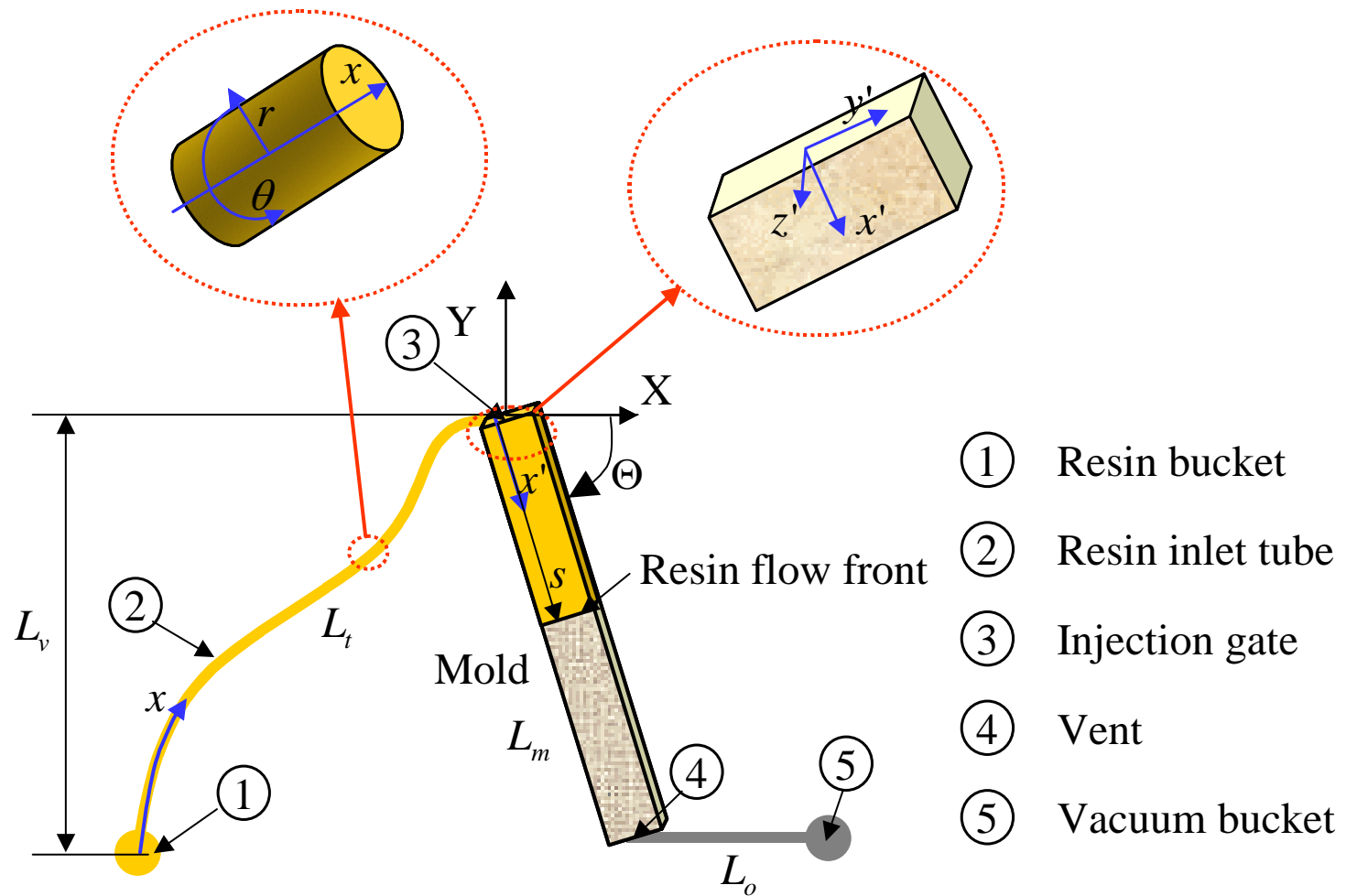
- ✓ Develop an analytic solution incorporating **gravitational effects** to predict flow and pressure distributions for tall structure VARTM processes in order to:
  - Obtain insight into the design and optimization
  - Minimize resin fill time
  - Estimate size limitation
  - Reduce dimensional tolerance



## APPROACH

- **Develop analytical models incorporating gravitational effects for 1-D. homogenous media**
  - ✓ **Assumption:**
    - Resin: Newtonian, incompressible, laminar, constant density and temperature
    - Reinforcement: homogenous with constant porosity and permeability
    - Tubing and preform have constant cross sections (no compaction)
  - ✓ **Parametric studies:**
    - Resin fill time
    - Mold angle
    - Permeability, length and cross section area of the preform
    - Length and radius of the injection tube
- **Experimental validation:**
  - ✓ Resin fill time (Flow front location)
  - ✓ Pressure distribution

# MODEL



## ANALYTIC SOLUTION I

### • Governing Equations:

#### • In the tube:

$$\frac{\mu}{r} \frac{d}{dr} \left( r \frac{du}{dr} \right) = \frac{\partial P}{\partial x} - \rho g_x$$

$$\bar{u} = -\frac{R^2}{8\mu} \left( \frac{dP}{dx} - \rho g_x \right)$$

$$P_i - P_r = -\rho g L_v - \frac{8\mu}{R^2} L_t \bar{u}$$

#### • Matching B.C. in the injection gate:

$$\bar{u} \pi R^2 = \phi \dot{s} W_m H_m$$

#### • In the preform:

$$u_D = -\frac{K}{\mu} \left( \frac{dP}{dx'} - \rho g_{x'} \right)$$

$$\phi \dot{s} = -\frac{\bar{K}}{\mu} \left[ \frac{P_o - P_i}{s} - \rho g \cdot \sin(\Theta) \right]$$

### • Closed Form Solution:

$$t = \frac{\phi \mu}{\bar{K} \rho g \sin(\Theta)} \left\{ s + \left[ \frac{8 \bar{K} W_m H_m L_t}{\pi R^4} - \frac{P_r - P_o}{\rho g \sin(\Theta)} + \frac{L_v}{\sin(\Theta)} \right] \cdot \ln \left[ 1 + \frac{s \rho g \sin(\Theta)}{P_r - P_o - \rho g L_v} \right] \right\}$$

## ANALYTIC SOLUTION II

- Dimensionless Parameters:

$$s^* = s / L_m, t^* = (P_r - P_o)t / \mu, k^* = \bar{K} / L_m^2, g^* = \rho g L_m / (P_r - P_o),$$

$$a^* = W_m H_m / L_m^2, r^* = R / L_m, l_v^* = L_v / L_m, l_t^* = L_t / L_m$$

- Nondimensionalized Equations:

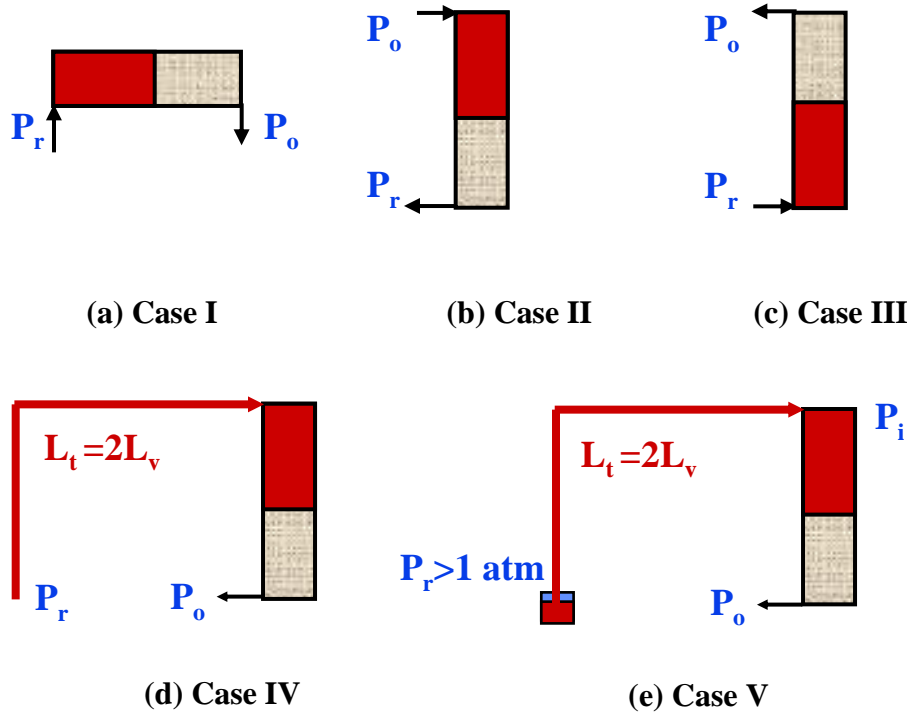
$$t^* = \frac{\phi}{k^* g^* \sin(\Theta)} \left\{ s^* + \left[ \frac{8a^* k^* l_t^*}{\pi(r^*)^4} - \frac{1}{g^* \sin(\Theta)} + \frac{l_v^*}{\sin(\Theta)} \right] \cdot \ln \left[ 1 + \frac{s^* g^* \sin(\Theta)}{1 - g^* l_v^*} \right] \right\}$$

$$t^* = \frac{\phi}{k^*} \left[ \frac{s^*}{g^*} - \frac{1}{(g^*)^2} \cdot \ln(1 + g^* s^*) \right] \quad \leftarrow L_t = L_v = 0; \Theta = 90^\circ$$

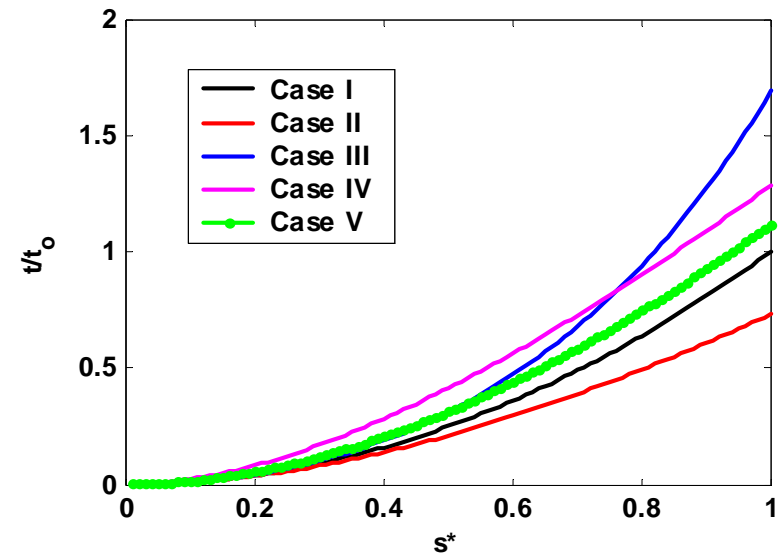
$$t^* = \phi \left[ \frac{(s^*)^2}{2k^*} + \frac{8a^* l_h^* s^*}{\pi(r^*)^4} \right] \quad \leftarrow L_v = 0; \Theta = 0^\circ; g^* = 0$$

$$t_o^* = \phi (s^*)^2 / (2k^*) \quad \leftarrow L_t = 0; \Theta = 0^\circ; g^* = 0$$

# INFUSION SCENARIOS



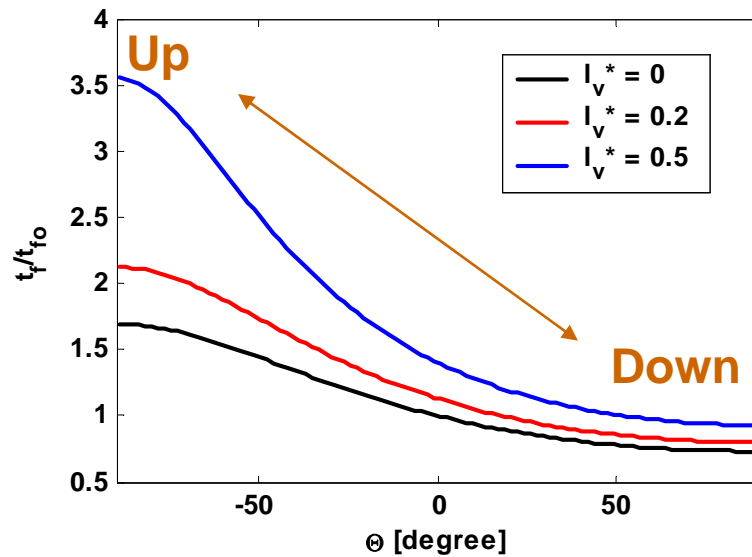
Flow Front Location vs. Fill Time



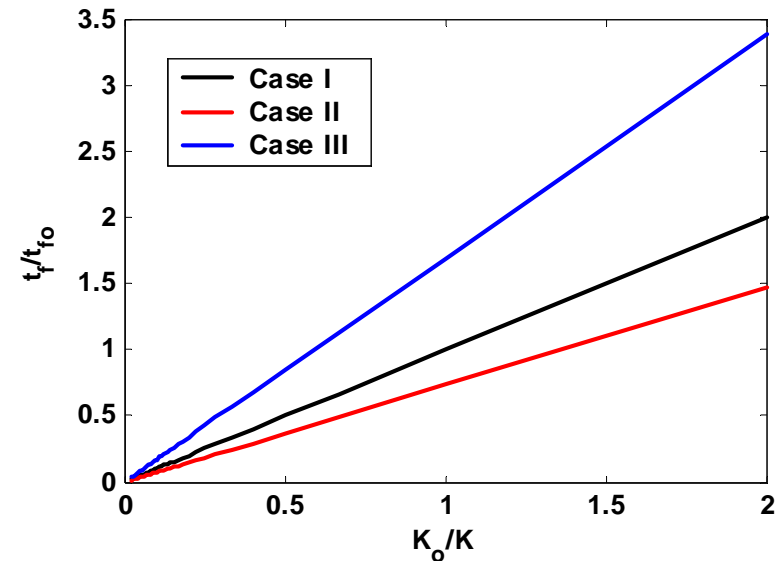
• Fill Times: Cases II < I ~ V < IV < III  
 (Hor. (I)=1.0, Down (II) = 0.75, Up (III) = 1.70)

## Infusion Scenarios

## PARAMETERIC STUDY II



Mold Angle vs. Fill Time  
( $L_t = L_v$ )



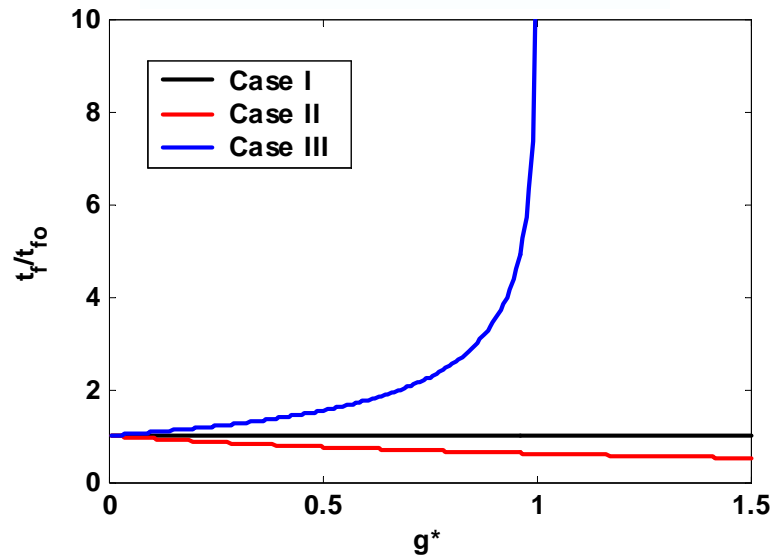
Reciprocal of Relative Permeability  
vs. Fill Time ( $L_t = 0$ )

- Increasing angle decreases fill time
- For upward infusion case, the tube head length affects significantly fill time
- For the downward infusion case, it does not play significant role

- Fill time depends linearly on  $1/K$  ( $K \rightarrow 2, t_f \rightarrow 0.5$ )

## PARAMETERIC STUDY III

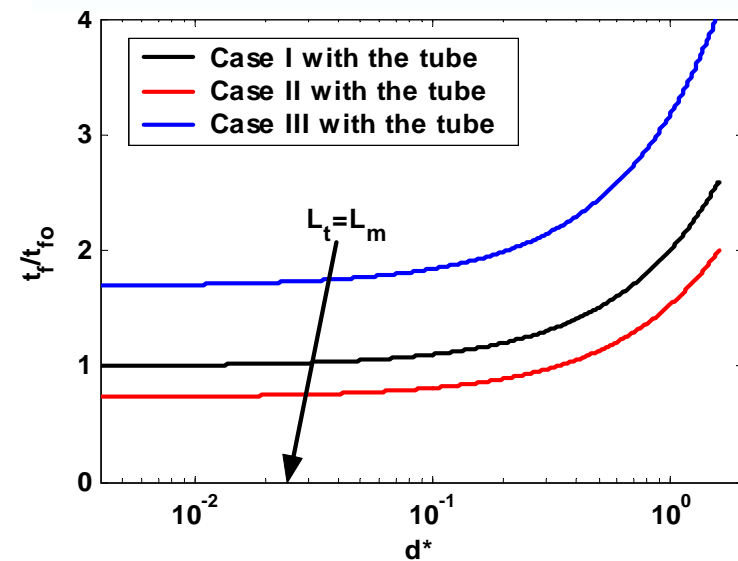
$$g^* = \rho g L_m / (P_r - P_o)$$



Dimensionless Gravity vs. Fill Time  
( $L_t=0$ )

- Limitation in the mold height for Case III
- No limit in the height for Cases I & II

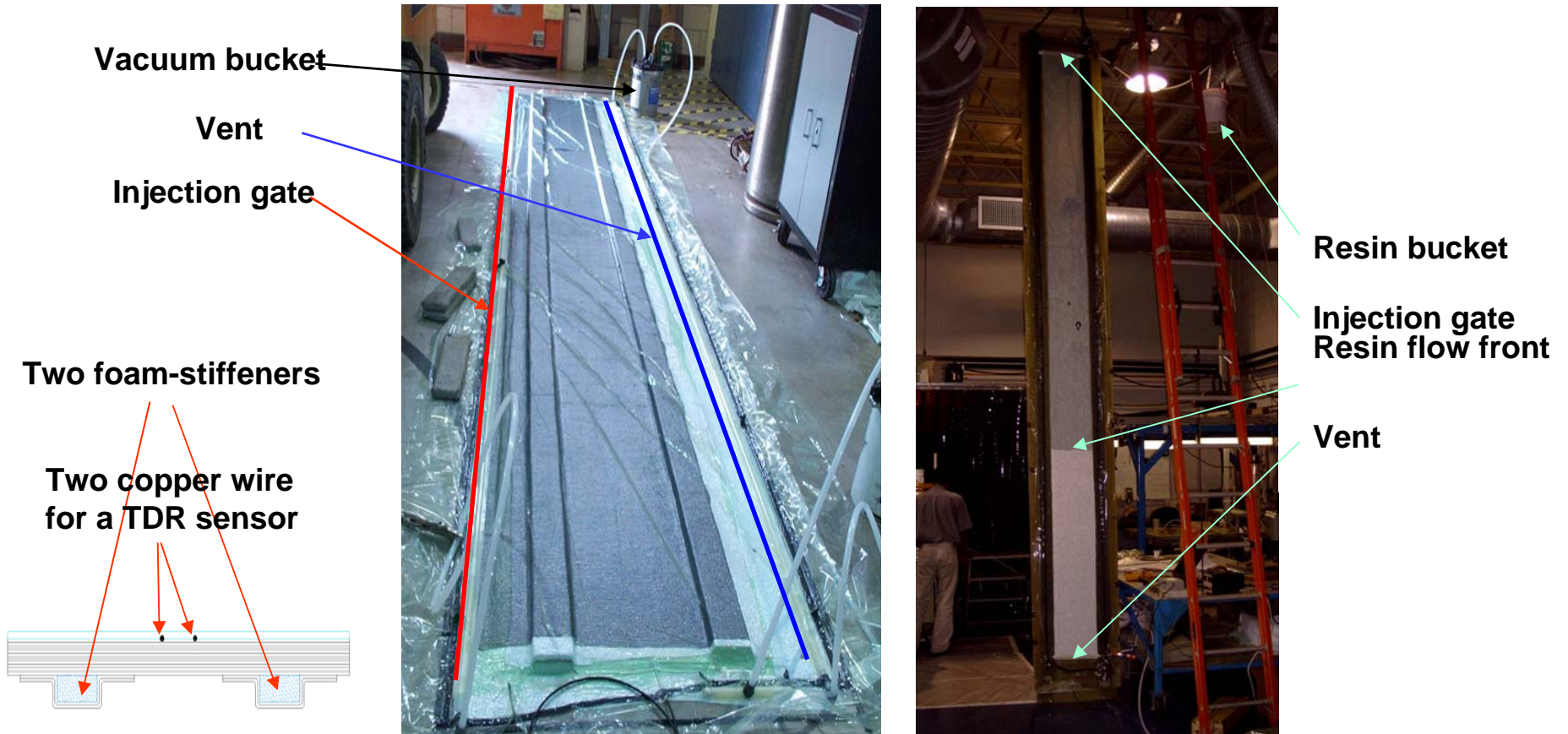
$$d^* = 16 \bar{K} W_m H_m L_t / (\pi R^4 L_m)$$



Dimensionless Relative Friction Loss Term  
vs. Fill Time ( $L_v=0$ )

- Fill time can be significantly increased for
  - Large cross section structures
  - Small radius tube (power of 4 influence !!!)
  - Long infusion tube
- Resin fill time of UD-CCM exp. setup is not

# EXPERIMENTAL SETUP



Cross section of the mold

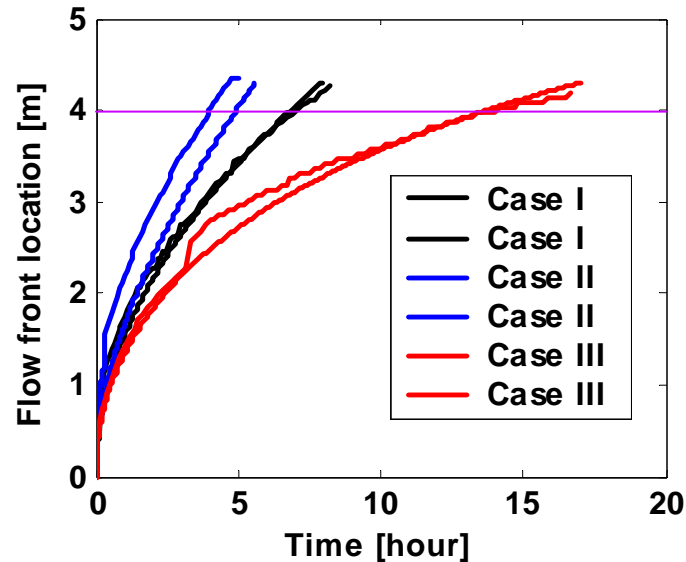
Mold manufacturing

Resin infusion downward

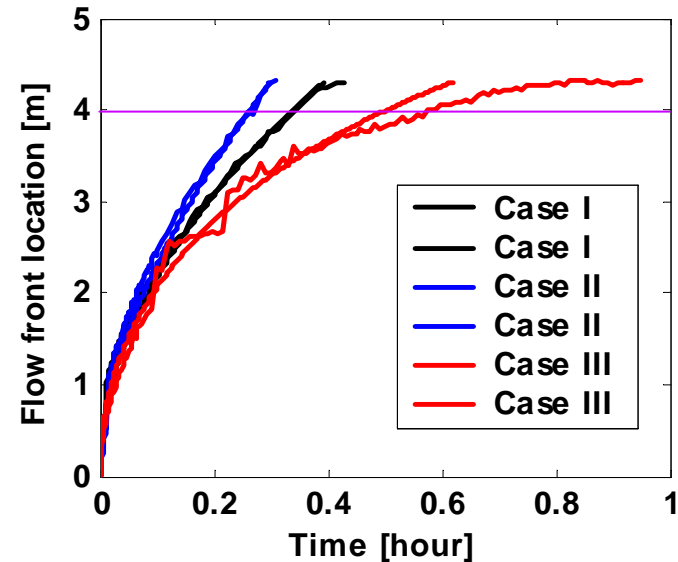
# RESIN FLOW FRONT LOCATION

(EXP. VS ANALYTICAL SOL.)

- Dotted lines show experimental results
- Solid lines show those from the analytic solutions.

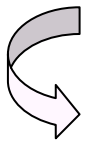


Random mat



Distribution media

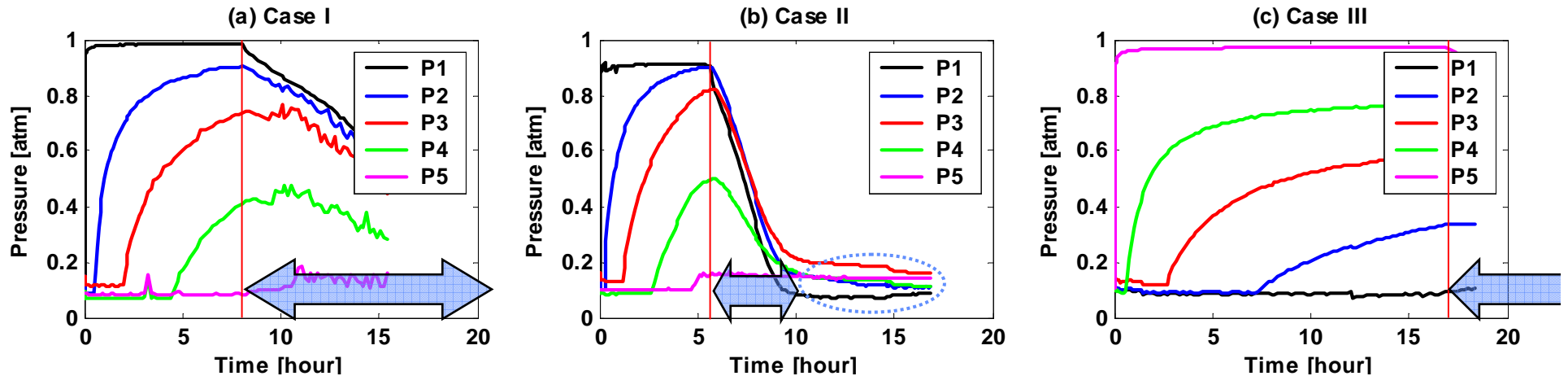
- Experimental results show good agreement with analytical solution
- Resin fill time at 4 meter mark:
  - ✓ Random mat: 7, 4.2, and 14 hours for Cases I, II, & III
  - ✓ Distribution media: 16, 12, and 35 minutes for Cases I, II, & III



# RESIN PRESSURE

(EXP. with Random mat)

- Vertical solid line shows the time when the injection gate was closed after each preform was fully impregnated
- Dotted circle shows the region when pressures are stabilized



- Resin arrival time:

**8 hr.**

**5 hr.**

**17 hr.**

- Pressure settling time:

**14 hr.**

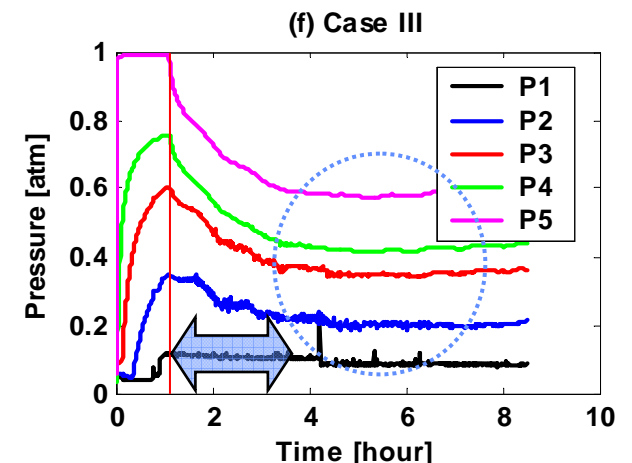
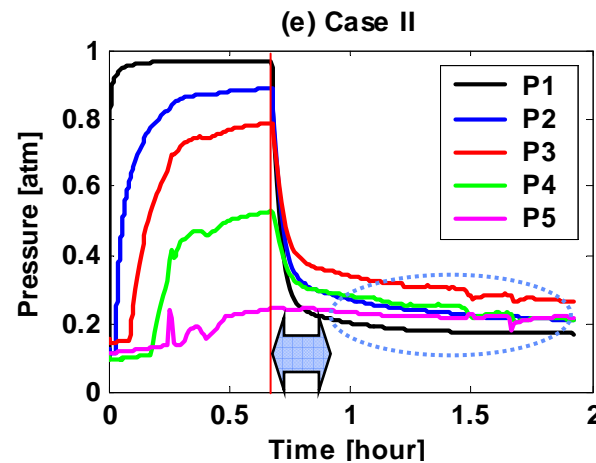
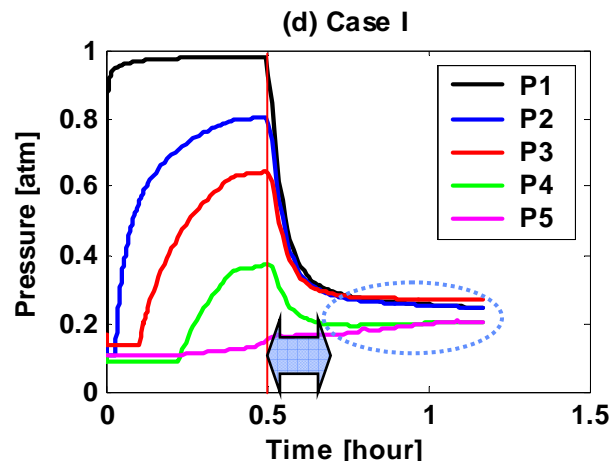
**4 hr.**

**25 hr.**

# RESIN PRESSURE

## (EXP. with Distribution media)

- Vertical solid line shows the time when the injection gate was closed after each preform was fully impregnated
- Dotted circle shows the region when pressures are stabilized



- Resin arrival time:

0.45 hr.

0.25 hr.

1.0 hr.

- Pressure settling time:

0.25 hr.

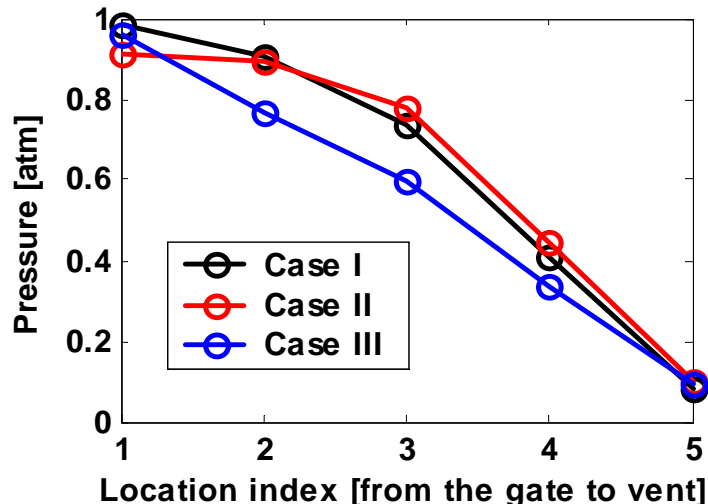
0.20 hr.

2.0 hr.

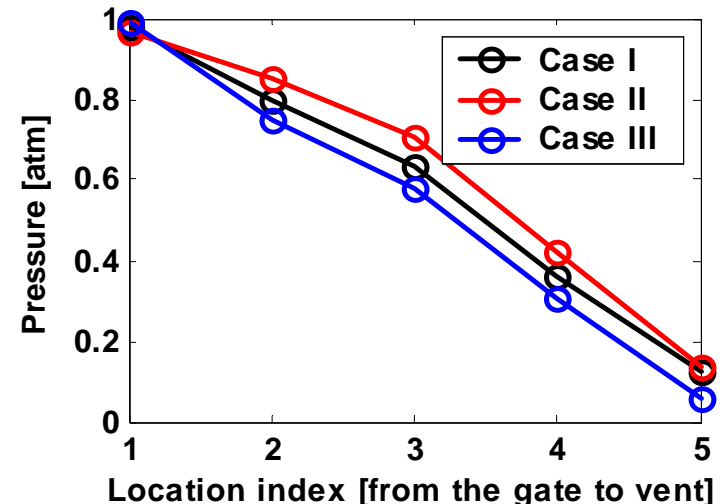
# RESIN PRESSURE DISTRIBUTION

(Exp. Results Before Gate Close)

- Just before closing of the injection gate



Random mat



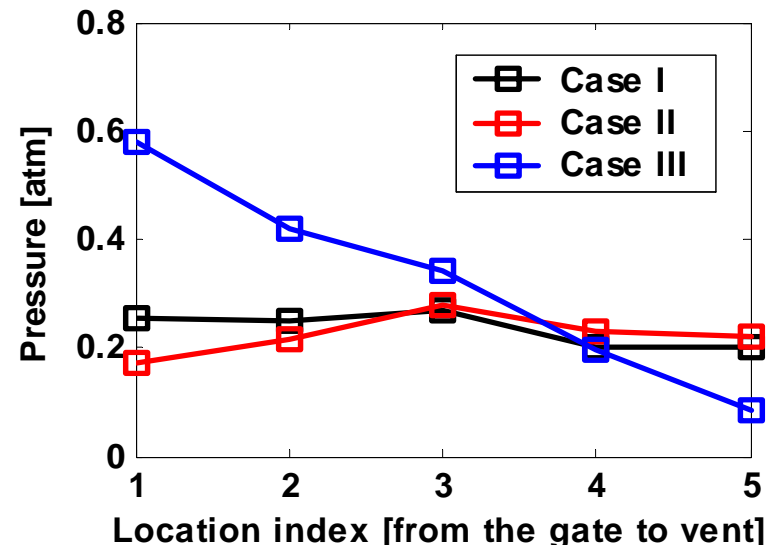
Distribution media

- Pressure gradient  $\sim$  Thickness variation ( $P \sim E\varepsilon$ )  $\rightarrow$  Dimensional tolerance
- The pressure distribution is close to linear (agreement with analytic model)

# RESIN PRESSURE DISTRIBUTION

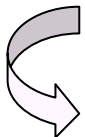
(Exp. Results After Pressure Stabilized)

- After pressure settling time



## Distribution media

- No thickness variation for Cases I and II
- Still thickness variation left for Case III (Upward infusion)
- Resin curing time should be controlled to ensure pressure settling time



## CONCLUSION

- **Developed a closed form equation incorporating gravitational effects**
- **Parametric study provided insight into the design and optimization of the VARTM process**
  - **Mold length and angle**
  - **Tube length and radius**
  - **Resin density and preform permeability.**
  - **Gravitational effects.**
- **Validated the analytic solution with experimental results**
  - **Flow front locations by TDR sensors**
  - **Pressure gradient by distributed pressure sensors**



Horizontal & downward injection cases showed better performance than upward infusion case in view of infusion time & thickness variations



## ACKNOWLEDGEMENT

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