UNIVERSITY OF DELAWARE
CENTER FOR COMPOSITE MATERIALS
INTERNATIONALLY RECOGNIZED EXCELLENCE

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MODELING VOID DRAINAGE WITH THIN FILM DYNAMICS

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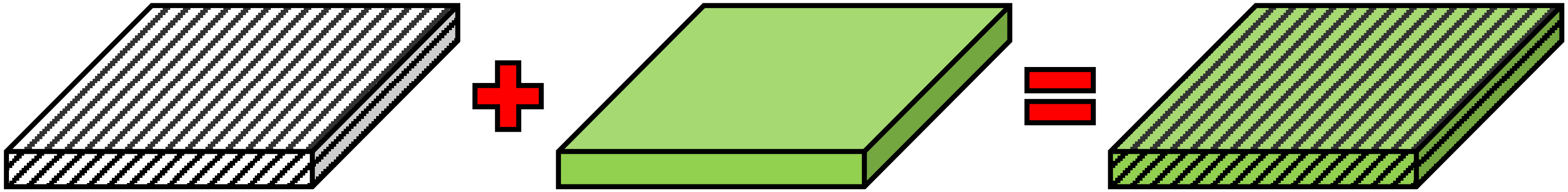
INTRODUCTION

- **What is a composite material?**
  - **i.e. Carbon/Glass/Aramid Reinforced Polymer**



- **Composite structure examples:**

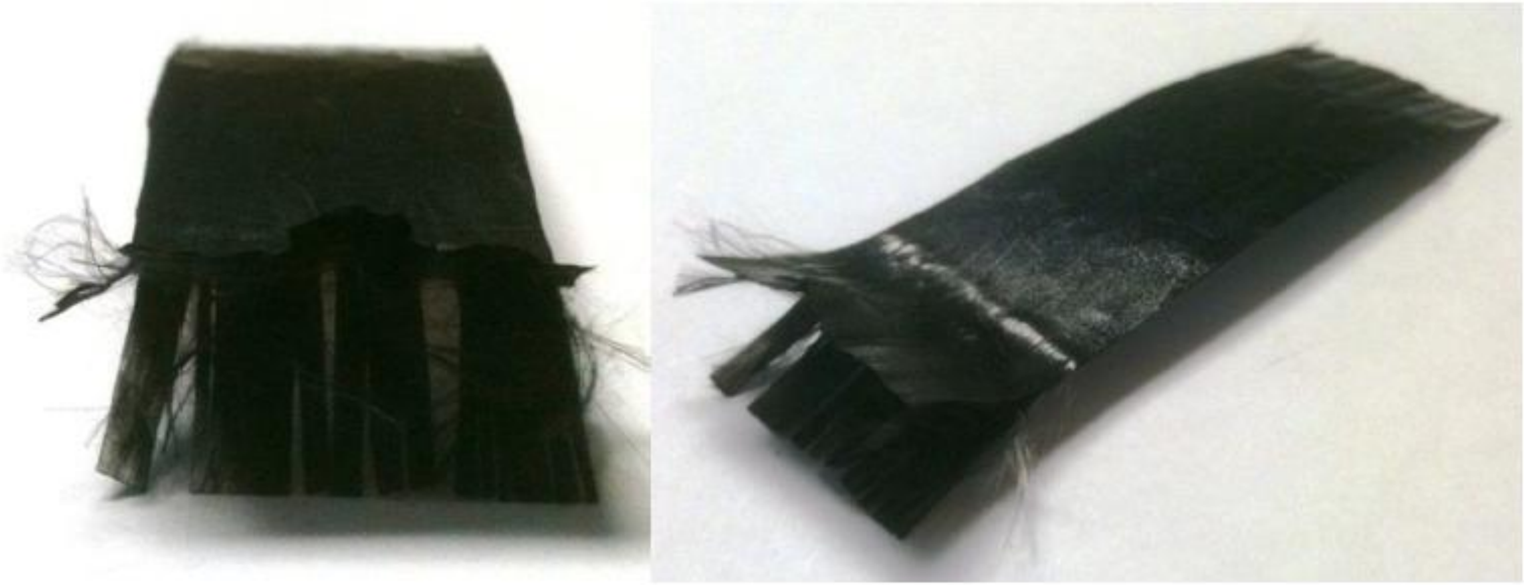
http://1.bp.blogspot.com/_lTVfb4qUtJk/TLtmXrThAvI/AAAAAAAAAc0/X242b8olUwQ/s400/Lamborghini-Sport-Cars-Lamborghini-Sesto-Elemento-Concept-7.jpg

http://www.businessinsider.com/batik-air-787-2012-6

http://en.wikipedia.org/wiki/File:Windmills_D1-D4_(Thornton_Bank).jpg

INTRODUCTION

- A prepreg is like a tape with unidirectional continuous fibers partially covered with a polymeric resin
- Pregregs are cut, stacked, and consolidated on a tool to form the shape of the desired structure



Partially impregnated composite prepreg tape sample with resin rich top and bottom surfaces (e.g. shiny surfaces of the tape within the figure) versus the fibrous dry center

INTRODUCTION

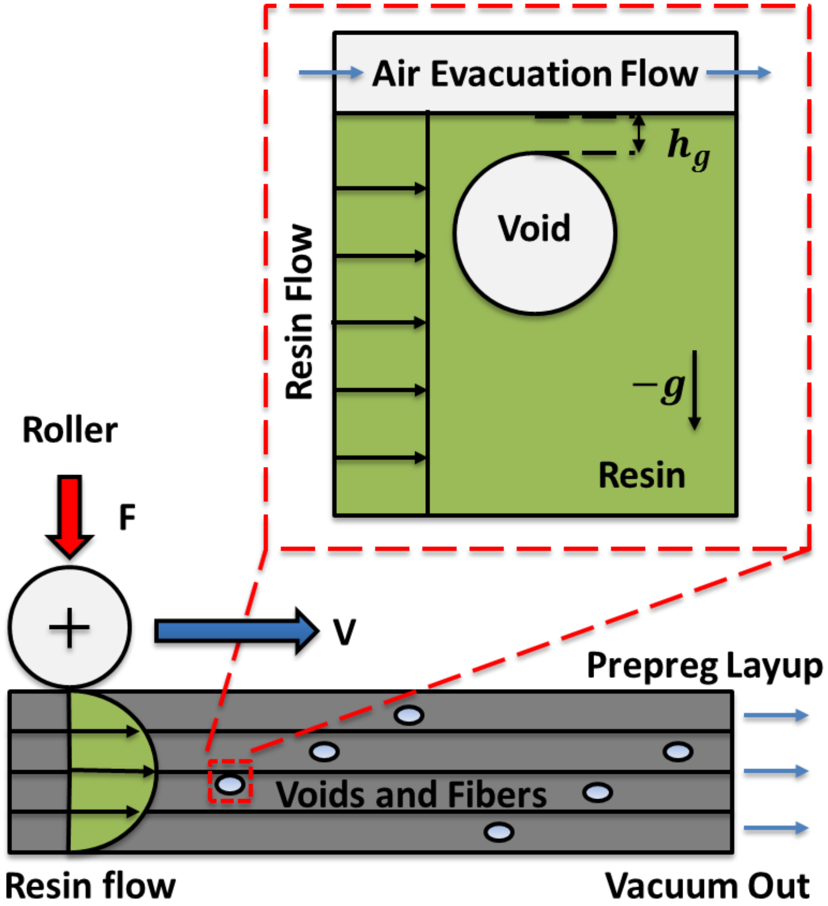
- Voids create stress concentrations within the cured composite
- Voids can compromise structural performance and reliability

Example of cured Out-of-Autoclave (OOA) prepreg composite with high void content*

*http://composites.usc.edu/projects/out-of-autoclave-processing-of-composite-prepregs.htm

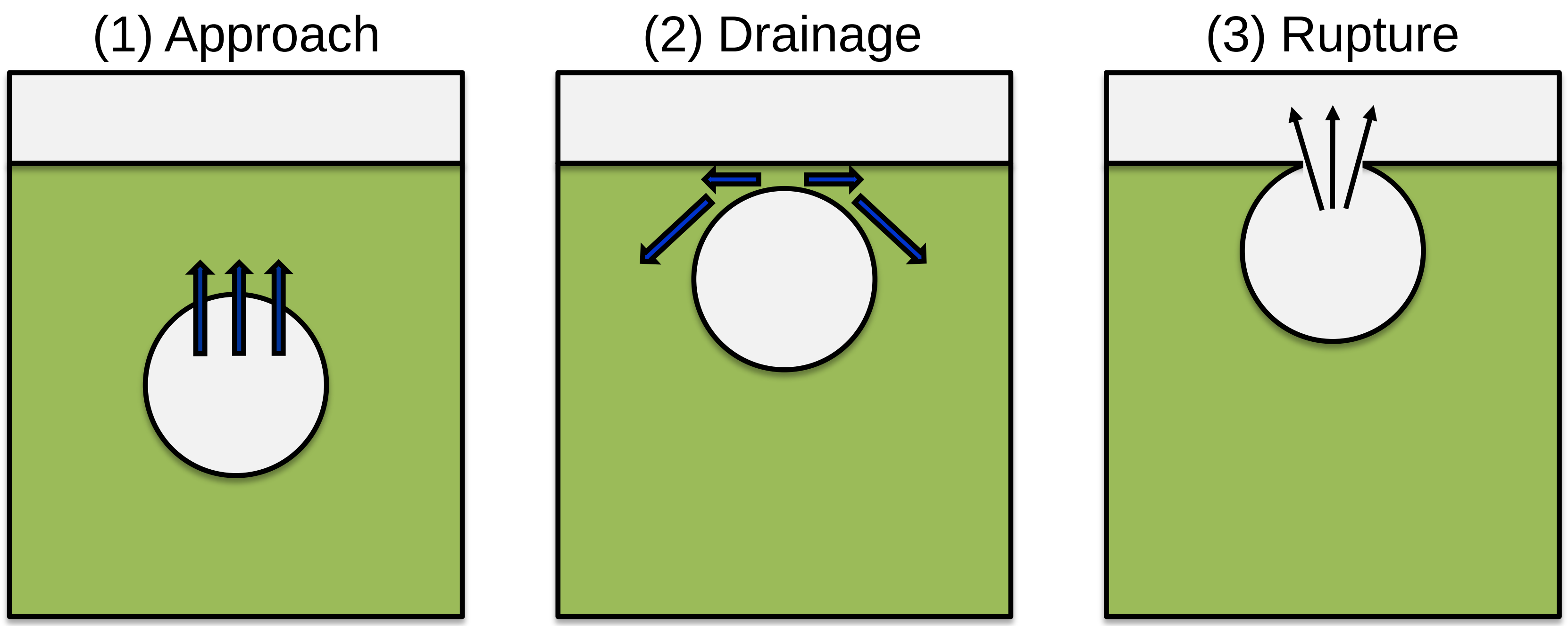
INTRODUCTION

- **Goal: Study voids in uncured polymer resin during prepreg processing**
- **Determine if voids can:**
  1. **Migrate to vacuum pathways**
  2. **Coalesce with pathways**
  3. **Escape in vacuum**
- **Focus on the *drainage* and *rupture* of formed resin films**
  - **Resin films around and inside fiber bundles**
  - **Focus on voids and resin free surfaces**
  - **Neglect fiber effects in this study**



THEORY

- **Coalescence of a single bubble with a free surface:**



- **Goal: To establish the *general trends* of void *approach* and *drainage* for understanding void *rupture***

THEORY

- **(1) Approach**
  - **Incompressible Navier-Stokes:**

$$\boldsymbol{\rho}\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \boldsymbol{u}\right) = -\boldsymbol{\nabla} p + \mu \boldsymbol{\nabla}^2 \boldsymbol{u} + \boldsymbol{f}$$

  - **Incompressible Continuity:**

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = \mathbf{0}$$

- **(2) Drainage**
  - **Exponential decay model*:**

$$h(t) = h_0 exp\left(-\frac{t}{\tau}\right)$$

$$\frac{1}{\tau} = \frac{\rho g a}{\mu}$$

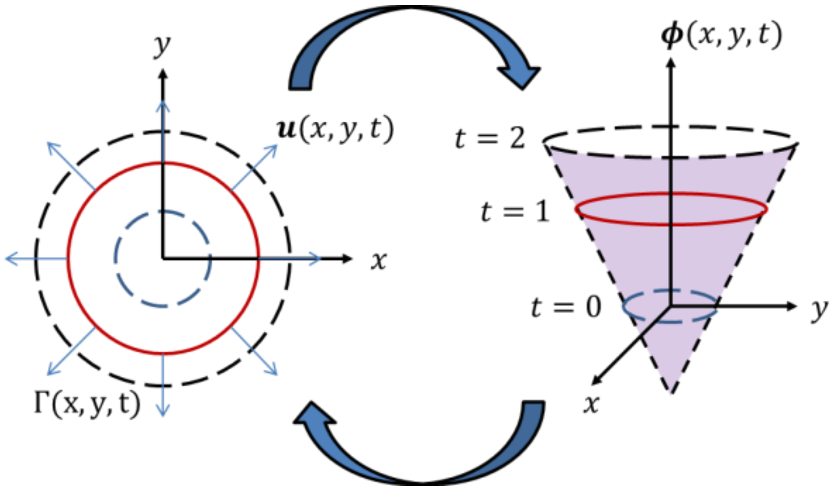
- **(3) Rupture**
  - **Bubble rupture velocity scale*:**

$$V_{br} \sim C\gamma / \eta$$

*G. Debrégeas, P.-G. de Gennes, F. Brochard-Wyart, The Life and Death of "Bare" Viscous Bubbles, Science, 279, 1704-1707 (1998)

METHODS

- Use *Level Set Method* (LSM) to calculate the void-resin interface with time
- Represent the interface with the a signed distance function
  - i.e. Level set function, ϕ
  - $|\phi(\boldsymbol{x})| = d(\boldsymbol{x}) = \min_{\boldsymbol{x_I} \in \boldsymbol{I}}(|\boldsymbol{x} - \boldsymbol{x_I}|)$
- Find interface by advecting level set function with time
  - Translates to a moving interface in Cartesian space
  - Level set reinitialization is performed for interface stabilization
- Easier computation than direct parameterization of the interface



GOVERNING EQUATIONS

Incompressible Navier-Stokes

- $\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}\right) = -\nabla p + \mu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{g} + \boldsymbol{F}_{sv}$

$F_{sv} \equiv$ surface tension contribution

Incompressible Continuity

- $\nabla \cdot \boldsymbol{u} = 0$

Level Set Equation

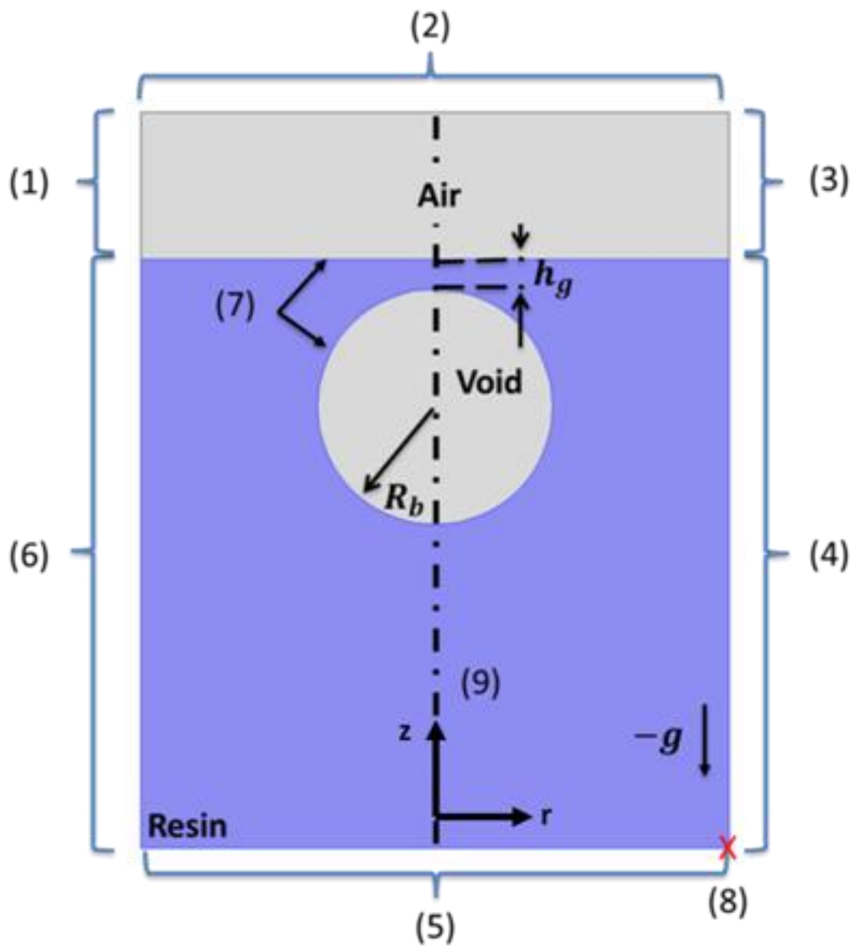
- $\phi_t + \boldsymbol{u} \cdot \nabla \phi = 0$

Material property smoothing over the interface for fluids 1 and 2	
Density	$\rho = \rho_1 + (\rho_2 - \rho_1) \cdot \phi$
Viscosity	$\mu = \mu_1 + (\mu_2 - \mu_1) \cdot \phi$

NUMERICAL MODEL

- COMSOL Multiphysics 4.2 + Microfluidics module is used for numerical solution
- Model a single spherical void in a cylindrical axisymmetric two-phase domain of resin and air
- The air domain is modeled as a fictitious fluid
  - The viscosity and density are 100 times smaller than resin
  - Avoids large magnitude differences in the stiffness matrix properties
  - Addresses the physical behavioral differences between air and resin
- Of interest is:
  - The *interface evolution in time* between resin and air
  - Influence of *surface tension* and *body force* between resin and void
    - Dimensionless Bond number: $Bo = \frac{buyoncy}{surface\ tension} = \frac{\rho g a^3}{3\gamma a}$

NUMERICAL MODEL



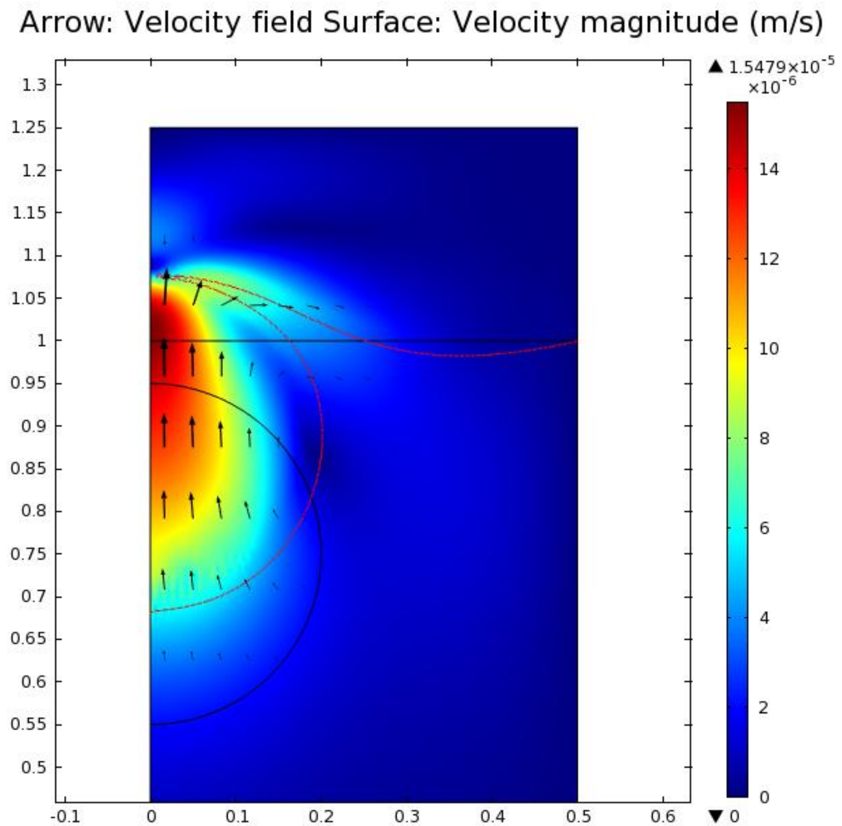
Parameters	Values
Domain width	1.00 mm
Domain height	1.25 mm
Air domain thickness	0.25 mm
Void radius, R_b	0.20 mm
Thin film thickness, h_g	0.05 mm
Interfacial tension, σ	0.03 N/m
Level set reinitialization, γ	0.001 m/s

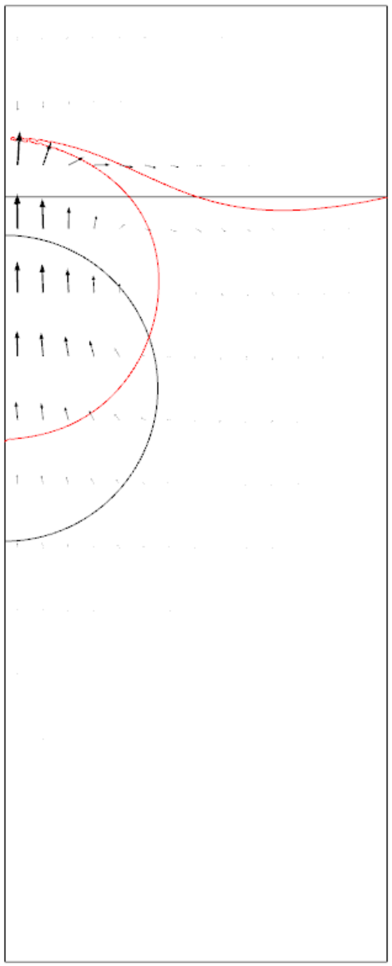
Phase	Density, ρ [kg/m^3]	Viscosity, η [Pa-s]
Resin	1000	10
Air	10	0.1

Edge ID	Boundary Condition
(1)-(6)	No slip wall
(7)	Initial air-resin interface
(8)	Pressure point constraint
(9)	Axis of Symmetry

RESULTS

- **Example:** $Bo = 1.0; t = 22.0\ s$





RESULTS

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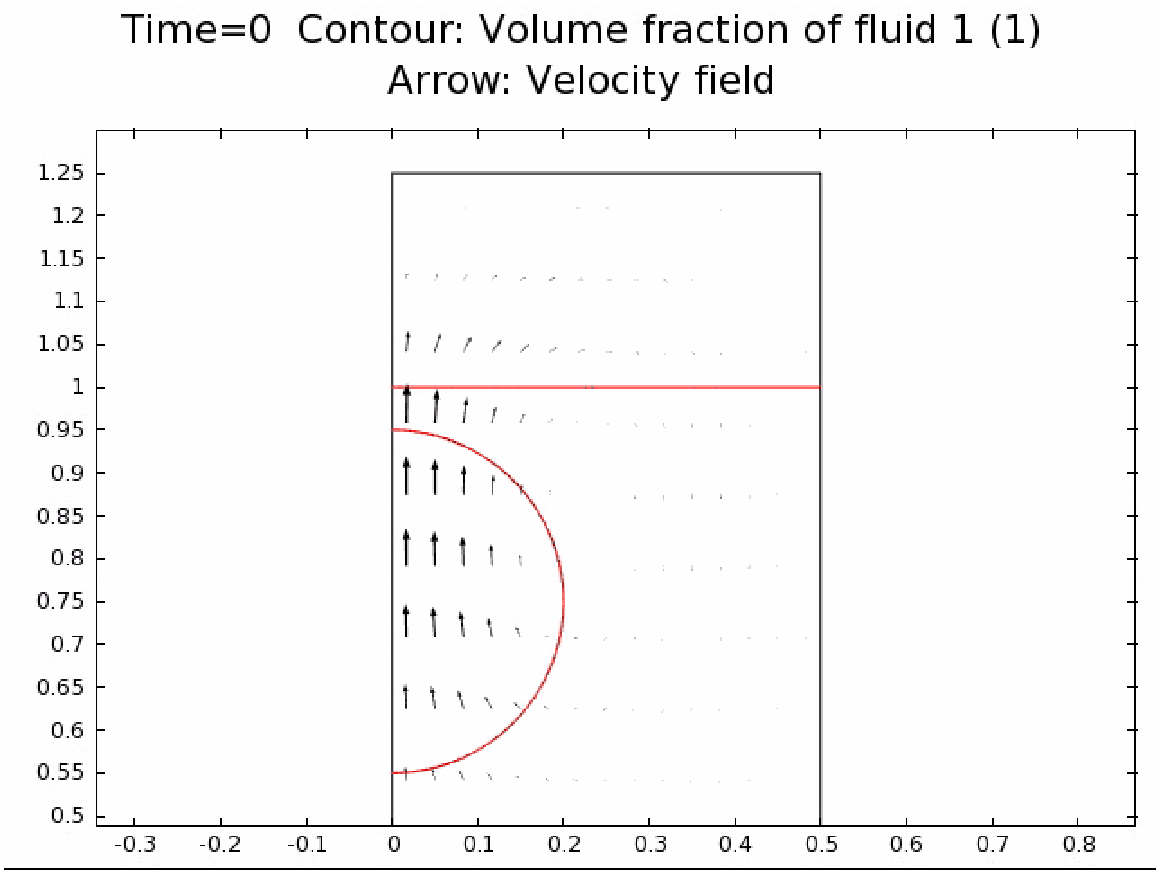
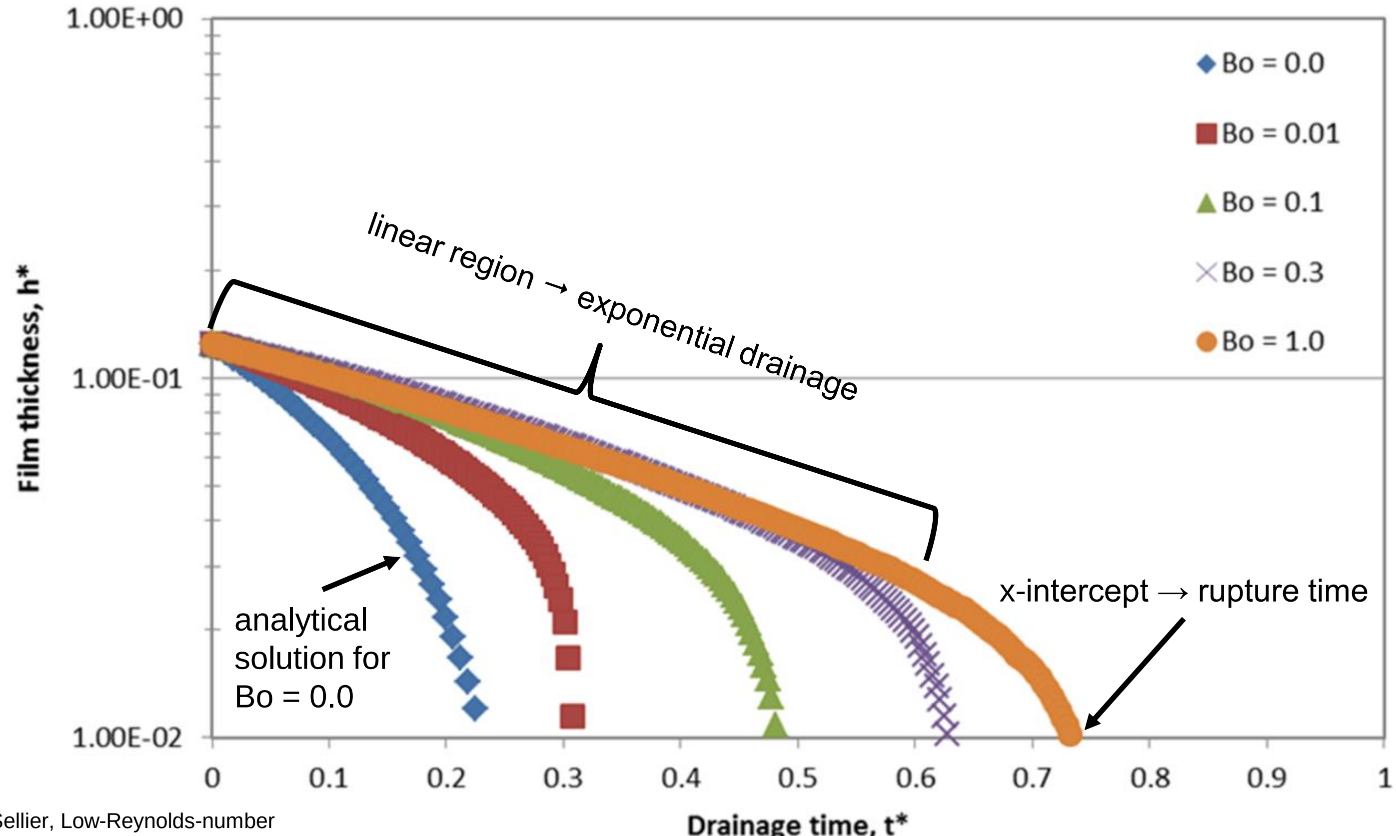


RESULTS

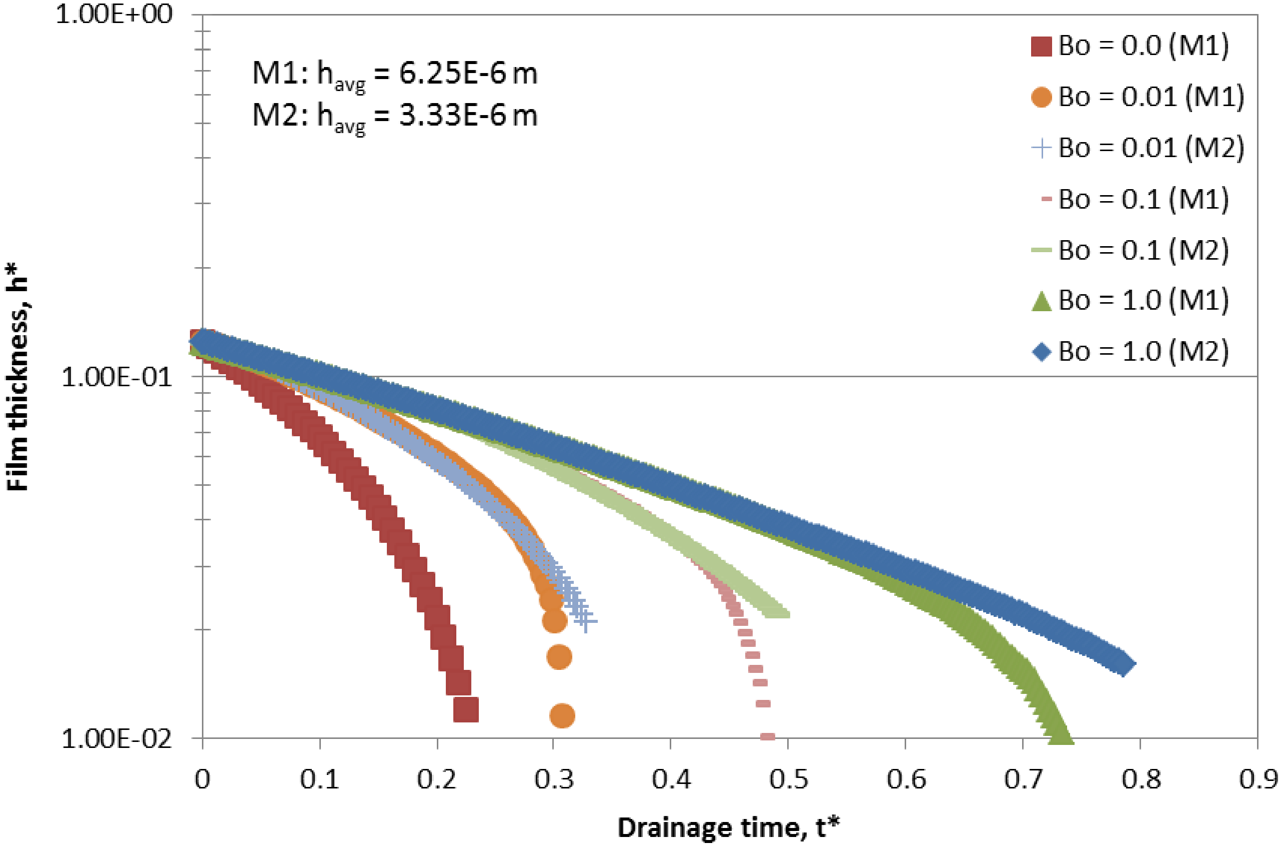
- Results agree with general trends found in Pigeonneau and Sellier (2011)*
- Non-dimensionalization: $h^* = h/2a\,, t^* = \rho g a t/6\mu$



* F. Pigeonneau, A. Sellier, Low-Reynolds-number gravity-driven migration and deformation of bubbles near a free surface, Physics of Fluids. 23 (2011).

RESULTS

- **Here the results are generated with two different mesh refinements**
  - **Labeled M1 and M2**
- ***Drainage time* is mesh dependent, but NOT *drainage trend***



DISCUSSIONS

- **LSM breaks down in accuracy as the film drainage progresses close to rupture**
  - **Film becomes thinner than the film element size**
  - **Leads to instability and artificial rupture during drainage process**
- **Can infer rupture time from drainage process time scale**
- **Exponential drainage trends from COMSOL were observed experimentally***

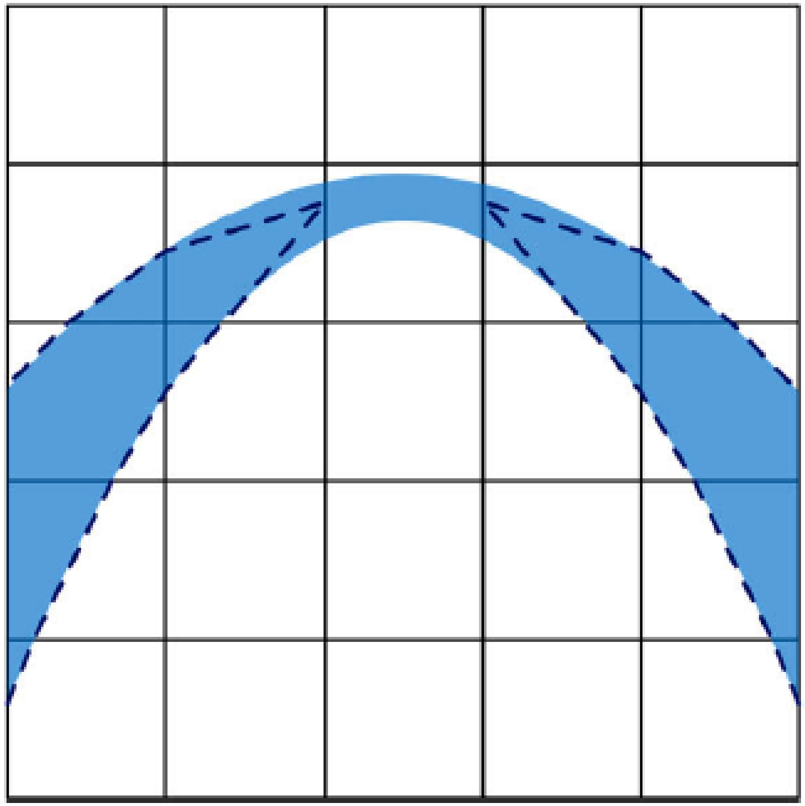


Fig. 1. Liquid film represented by level set method. The shadowed part is the actual film region, and the dashed line is the level set representation. The thinnest film is lost.**

*G. Debrégeas, P.-G. de Gennes, F. Brochard-Wyart, The Life and Death of "Bare" Viscous Bubbles, Science, 279, 1704-1707 (1998)

**W. Zheng, J.-H. Yong, J.-C. Paul, Simulation of bubbles, Graphical Models. 71 (2009) 229–239.

CONCLUSIONS

- **Void dynamics were found to be strongly dependent on void body force and surface tension effects as characterized by Bo**
- **Results suggest that resin film drainage at the interface with the bubble can be successfully modeled as an exponential decay**
- **Results are suspect once the film becomes thinner than the film element size**
- **Knowledge of film drainage information can provide insight into void removal efficiency during composite prepreg processing**

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