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Mathematical Modeling and Simulation of Wind Mill Blade Manufacturing (VARIM) Process

Yash Chawla[1], Vishnu Agarwal[2]

[1]Yash Chawla, Renewable Engineering, Geetanjali Institute of Technical Studies, Udaipur, Rajsthan, India

[2]Prof. Vishnu Agrwal, Mechanical Engineering Department, Geetanjali Institute of Technical Studies, Udaipur, Rajsthan, India

Abstract: ***This paper presents the manufacturing of wind turbine rotor blades using VARIM (Vacuum Assisted Resin Injection Moulding). Vacuum assisted resin infusion techniques have become popular in manufacturing of these composites. In this process, resin is drawn into a preform through use of a vacuum, rather than pumped in under pressure. It has become today's technology due to its low cost tooling also it has a wide application in large structures. It also reduces volatile organic compounds (VOCs) emissions. The resin is infused into the preform. The basic concept of infusion is to "suck" a resin into the reinforcing fibres and fabrics by a vacuum. The vacuum decreases the pressure at one end of the fabric stack allowing atmospheric pressure to force the resin over the fibres. The main process defects are caused by the possible in homogeneities in the fibre mat, or its improper installation. This will lead to the race tracking, which represents the main for all resin molding processes. In race tracking the movement of the fluid at both mold sides, or at one side only, with higher permeability regions, is more than the bulk of the fluid. Race tracking can start to the formation of macro-voids (dry spots) in the molded composite part during manufacturing. To solve it we first prepare a mathematical model (based on fluid flow properties and material properties) and then we use COMSOL multiphysics software in which the Navier-Stokes equation has been discretized by the finite element method as well as the level set equation.***

Keywords: Varim, Infusion, dry-spot

1. Background

Fibre-reinforced composites manufacturing has grown from modest beginnings to become a $55 billion, 7 million-ton global industry over the last three decades. Fibre-reinforced composites (FRCs) have been used in low-volume applications in space, military, and automotive industries during the last three decades of the 20th century. However, the first decade of the 21th century has seen a spectacular growth both in the volume and in the various of applications for FRCs. With the development of carbon-fibre composite airframes for the Boeing 787 and Airbus A350, leading aircraft manufacturers are gearing up for volumes of production never experienced before. At the same, the automotive industry is proposing to produce carbon-fibre chassis for high volume cars. Meanwhile, the wind energy industry is using a very large volume of composite materials for turbine blades, and the marine industry has been involved in building large boats and ship structures using advanced composites.

The FRC technology is now confronting a step change similar encountered by the semiconductor industry in the 1970's. The modern demand is such that the manufacturing process can no longer rely on design updates based on *adhoc* considerations and crude simulations. It must now base itself on more fundamental mathematical models and efficient numerical implementation. [1]

Advanced composites manufacturing has three distinct processing stages:
(a) Preforming: a number of fabric plies are laid-up in preferred orientations and formed/draped into the required shape. Individual ply may be a dry fabric layer or pre-impregnated with resin.
(b) Resin infusion: dry fibre preform is infused with a suitable low-viscosity resin before consolidation.
(c) Solidification: the infused fabric is consolidated in an autoclave under heat and pressure. [2]

2. Approach

In this project the manufacturing of wind turbine rotor blades using the advanced composite materials is considered. The efficiency of the wind turbine depends on the material of the blade, shape of the blade and angle of the blade. So, the material of the turbine blade plays aimportant role in the wind turbines. The properties of blade material should be high stiffness, low density and long fatigue life. These properties are provided by the advanced composite materials; furthermore, they possess dimensional stability, temperature and chemical resistance, and relatively easy processing. A various manufacturing methods can be used according to the design requirements. As an industrial application composites uses a polymer matrix with textile reinforcements such as glass, aramid and carbon. The main structural materials of a rotor blade are glass fibre, infusion resin system, structural adhesive and structural core: balsa or PVC foam.

Vacuum assisted resin infusion techniques have become famous in manufacturing of these composites. We use here the acronym VARIM coming from the words Vacuum Assisted Resin Injection Moulding. [3]

The main steps of the process are:
a) A dry fabric or preform and structural core materials such as balsa or PVC foam are arrange on tool surface.
b) The preform is airtight with a vacuum bag and the air is evacuated by a vacuum pump.

c) Liquid resin with hardener from an external reservoir is peaked into the component by vacuum. The liquid resin with hardener is infused into the preform up to complete impregnation.
d) Curing and de-moulding steps follow the impregnation to finish the product.

The components of the infusion process utilized in this work are illustrated in Figure 1.

We concentrate here on the process step (c), where the resin is infused into the preform. The basic concept of infusion is to "suck" a resin into the reinforcing fibres and fabrics by a vacuum. The vacuum decreases the pressure at one end of the fabric stack allowing atmospheric pressure to force the resin over the fibres.[4]

The fabric stack infusion depends on following parameters:
- The viscosity μ of the resin;
- The permeability k and porosity m of the fabric stack;
- The pressure gradient δp acting on the infused resin.

A general principle for the relationship between these parameters and the speed of the infusion process is given by the equation,

$$v = \frac{k \cdot \Delta p}{\mu}$$

In short, one should use very low-viscosity resin, high pressure gradient and fabrics with high permeability. However, the fabrics are mainly selected for their mechanical performance and the direction of fibres. Also the geometry of the infusion area as well as the number and location of the vacuum outlets controls the resin inflow into the fabric.

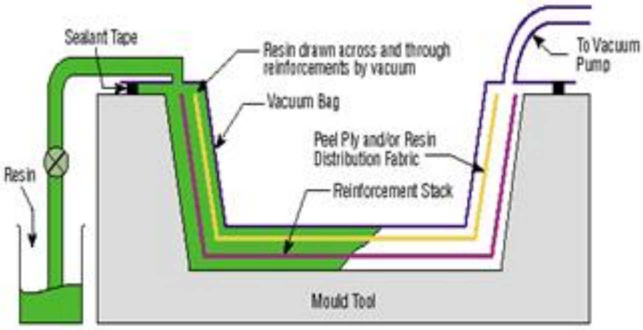

Figure 1: Infusion process

The main process defects are caused by the possible in homogeneities in the fibre mat,or its improper installation. This will lead to the race tracking, which represents the main for all resin molding processes. In race tracking the movement of the fluid at both mold sides, or at one side only, with higher permeability regions, is more than the bulk of the fluid. Race tracking can start to the formation of macro-voids (dry spots) in the molded composite part during manufacturing.

3. Mathematical Modeling

Following [1] we model the resin flow through the fibre and structural core system as a two-phase fluid flow by porous media. For the model we have adopted the following simplifications:
1) The properties of resin do not change and no curing takes place during the isothermal infusion process.
2) Capillary and inertia effects are ignored. [5]

We assume that during the infusion process the domain Ω, which is bounded by themold and the vacuum bag, is fixed. The fraction of volume occupied by resin at time $t$is denoted by $\Omega_{resin}(t)$ and by air $\Omega_{air}(t)$. The interface between resin and air is $\Gamma_{Int}(t)$.

Hence the domain is divided in three non-intersecting parts $\Omega = \Omega_{resin}(t) \cup \Omega_{air}(t) \cup \Gamma_{Int}(t)$.

The location of the interface is provided by the level set function

$$\phi(x,t) = \begin{cases} 1, \ \mathrm{x} \ \in \Omega_{resin}(t) \\ \text{-}1, \ \mathrm{x} \ \in \Omega_{air}(t) \end{cases}$$

The flow through the glass fibre depends on the porosity m and the permeability tensor $K = (kij)i,j=1,\ldots,d$.

The unknowns of the problem are the velocity field of the resin $\mathrm{v} \in \mathrm{R}^d$ the pressure p and the evolution of the interface $\Gamma_{int}(t)$. We have used d for the dimension of the problem depending whether the problem is simulated in full three-dimensional setting (d = 3) or in two-dimensional case (d = 2).

In the two-phase fluid flow the momentum equation is given by

$$\rho\left(\frac{dv}{dt} + (\nabla v)v\right) + \nabla p - div\left[2\mu(\phi)\varepsilon(v)\right] = b,$$

where $\varepsilon(v) = \frac{1}{2}(\nabla v + (\nabla v)^T)$ is the strain deformation rate and the external body forces, b, are due to the pressure losses (Darcy law). Here we have assumed that the properties of the resin and air remain constant during the infusion process and no curing take place.

Hence the density and viscosity of the resin-air system is given by,

$\rho = H(\phi)\,\rho_{resin} + (1 - H(\phi))\,\rho_{air}$

$\mu = H(\phi)\,\mu_{resin} + (1 - H(\phi))\,\mu_{air}$

at every time instant, where H is the Heaviside step function.

The standard assumption here is the incompressibility of the fluids: $div(\mathbf{v}) = 0$. The mass transport is governed by the level set equation (movement of the interface):

$$\frac{d\phi}{dt} = v \cdot \nabla\phi$$

The body forces due to the pressure loss are given by

$$b = \begin{cases} \mathrm{b_{gf}}, \ \text{in } \Omega_{gf} \\ \mathrm{b_{sl}}, \ \text{in } \Omega_{sl} \end{cases}$$

Where Ω_{gf} denotes the subset of Ω corresponding to fiber glass and Ω_{sl} the remaining part that corresponds to narrow slits. The pressure loss due to the fiber glass is modeled by the relation

$$b_{gf,i} = -\sum_{j=1}^{d} \frac{\mu m}{k_{ij}} v_i, i = 1, ..., d,$$

according to the Darcy law, where the permeability tensor $K = (kij)i,j=1,...,d$ depends on the orientation of the fibres in the fibre mat.

Since the resin flows through the narrow slits or channels between the balsa blocks,it causes a pressure loss (race tracking)

$$b_{sl,i} = -\frac{\mu}{k_{race}} v_i, i = 1, ..., d,$$

The equivalent race tracking permeability of the slits in balsa, k_{race}, depends on the slits height, h, and width, w, and is given by the relation

$$K_{race} = \frac{h^2}{12}\left(1 - \frac{192h}{\pi^5 w} - \sum_{i=1}^{\infty} \frac{\tan(2i+1)\pi w/2h}{(2i+a)^5}\right)$$

In the beginning before opening the valve the velocity of the fluid is zero:$v(x, 0) = 0$,the pressure inside the mold is the vacuum pressure $p(x, 0) = p_v$ and the domain is filled with air. In other words, $\Omega_{air}(0) = \Omega$ so, $\phi(x, 0) = -1$.

The boundary conditions are as follows:

- on the inlet boundary, Γ_{inlet}, where the mold is connected with the resin source, the pressure is the atmospheric pressure : $p(x, t) = p_a$
- on the outlet boundary, Γoutlet, where the mold is connected with a vacuum pump, the pressure is the vacuum pressure : $p(x, t) = p_v$
- on the remaining parts of the outer boundary, $\partial\Omega \setminus (\Gamma_{inlet} \cup \Gamma_{outlet})$, a no-slip boundary condition is considered:

$$b = \begin{cases} v \cdot n = 0 \\ \sigma_t = 0 \end{cases}$$

Where σ_t is the shear stress.

- on the interface $\Gamma_{Int}(t)$: $\sigma_{resin}\mathbf{n} - \sigma_{air}\mathbf{n} = \sigma\ k\ \mathbf{n}$, where σ denotes the surface tension, the unit normal vector can be computed as $\mathbf{n} = \frac{\nabla\phi}{|\nabla\phi|}$ and the curvature $k = \mathrm{div}(\mathbf{n})$.

We have used the COMSOL multiphysics software in which the Navier-Stokes equation has been discredited by the finite element method (FEM) as well as the level set equation.

The advantages of the level set method rely on its capability to capture topological changes. The intrinsic geometric properties are easy to determine and it is relatively easy to implement. In some cases accurate high order computational schemes exist. However, the existent high order schemes require quite a lot of tuning.

On the contrary, it is computationally expensive and requires re-initialization procedure every few time steps to maintain the signed distance function. It is not conservative, i.e. loss or gain of mass is observed due to numerical diffusion. Finally, for high contrast fluids the performance is not so good. [6]

4. Numerical Results

The mathematical model proposed in Section 3 was simulated using the COMSOL multiphysics software. To simplify the numerical simulation and keep in reasonable calculation times, accordance with the duration of these study groups, we performed a simulation assuming an axis symmetry hypothesis that is, assuming that Ω is a cylindrical domain with $r = 201.75mm$ and $z = 31mm$. The computation domain, which corresponds to across section in the plane r, z, is detailed in Figure 2.

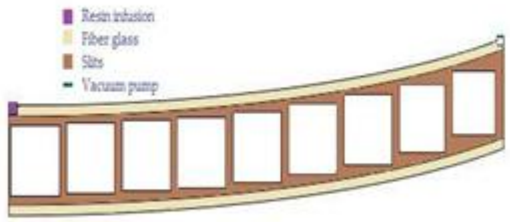

Figure 2: Computational domain.

The conservative level set method, which is carry out in the finite-element based solver COMSOL Multiphysics, is used here to simulate incompressible two-phase flows(resin-air), where gravity and surface tension effects are added. However, the effects of porosity have not been considered in the results presented in this section. Figure 3 shows the triangular meshing of the domain with 2697 elements. An adaptive mesh has been used so we can observe a greater refinement in the resin inlet and vacuum area.

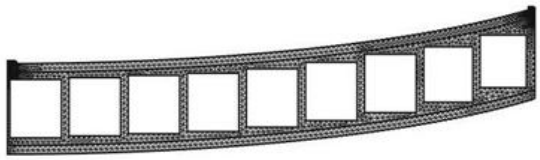

Figure 3: Triangular mesh of the Domain.

The following figures show the evolution of the level set function, obtained through the volume fraction of air and, therefore, as the resin flows at the initial time and after 0.01s,1s and 2s. It can be seen that, by not considering the porosity of the fiberglass, the resine flows faster through this area of the upper, it has difficulty crossing the narrow channel between the balsa and to access the bottom of the domain.

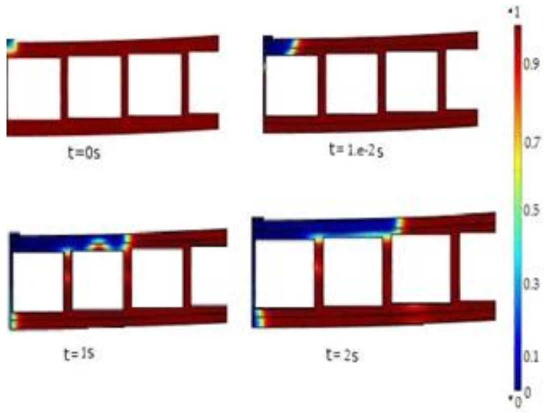

Figure 4: Volume fraction of air at the initial time and after 0.01s, 1s, and 2s.

5. Conclusion

In this report it has proposed a complete mathematical model representing the behavior of the injection of resin into a mold to obtain a wind turbine blade. The associated model corresponds to a system of partial differential equations which couple the Navier Stokes equations, to modelize the advancing of the resin, with the transport equation, to follow the interface between the resin and air in the inner of the mould. In addition, the fiber glass and the narrow channels in the balsa are included in the model using laws of Darcy type. Due to the complexity of the problem, and the limited time of the conference, this report only presents the numerical simulation for a simplified model in which the terms derived from Darcy's law have not been incorporated; the incorporation of these terms is not difficult but requires slight modifications over the standard models of the software package used, which will be the subject of a future work.

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