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In

SOLID AND STRUCTURAL MECHANICS

# **Process Modeling of Composite Manufacturing**

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Gothenburg, Sweden, 2013

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Process Modeling of Composite Manufacturing  
Thesis for the degree of licentiate of engineering in solid and structural mechanics  
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## **ABSTRACT**

The focus of this research thesis is toward developing a framework for holistic modeling of composites manufacturing of fiber reinforced structural composites. The processes that have been considered are Liquid Composite Molding (LCM) and Out Of Autoclave (OOA) processes, ranging from Liquid Resin Infusion (LRI) and Resin Transfer Molding (RTM) in LCM processes, to Vacuum Bag Only (VBO) and Evac prepregs in OOA processes. To develop this framework the theory of two phase porous media has been extensively used and developed. A finite element formulation and implementation of the two phase problem has been developed for compressible-incompressible constituents using Taylor-Hood element assuming hyper-elastic material response for the fiber bed. The issues that are considered during the simulations are analysis of process physics such as (1) modeling the highly deformable preform and the shape of the membrane due to the considered loading conditions, (2) the free surface problem when the flow front is moving with respect to a flow front velocity into the vacuum zone of the porous media, (3) the coupling effects between macro-scale preform processes and meso-scale ply processes, (4) development of an anisotropic permeability model, (5) coupling effects between the solid and fluid phases.

The proposed formulation has been implemented and numerical results are provided for both cases of LCM and OOA processes. As a main result a coupled displacement-pressure, geometrically non-linear, finite element simulation tool is developed. Numerical examples of an infusion problem of a hat-beam, simulating both RTM and LRI, and also a relaxation-compression test of a planar fluid filled VBO preform, for LCM and OOA processes respectively, are considered.

Keywords: Poro-Mechanics; Finite element Analysis (FEA); Manufacturing Technologies; Polymer Composites.



*To my beloved family*



## **PREFACE**

The work presented in this thesis is carried out at the department of Applied Mechanics, division of Material and Computational Mechanics at Chalmers University of Technology during January 2011-January 2013. The work is also partly funded and carried out at the Swedish Research Institute of Composite Material, Swerea SICOMP, from February 2012.

I would like to thank my supervisor professor Ragnar Larsson and co-supervisor assistant professor Maciej Wysocki for their support and guidance during this time. I would not be able to come this far if they would not be patient and helpful.

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Mohammad S. Rouhi

February 2013





# THESIS

This thesis consists of an extended summary and the following appended papers:

- Paper A** Larsson R. **Rouhi, M.S.**, Wysocki, M., “Free surface flow and preform deformation in composites manufacturing based on porous media theory”, *European Journal of Mechanics A/Solids* 31 (2012) 1-12
- Paper B** **Rouhi, M.S.**, Wysocki, M., Larsson, R., “Modeling of coupled dual-scale flow–deformation processes in composites manufacturing”, *Journal of Composites: Part A* 46 (2013) 108–116



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# I Extended Summary

## 1 Introduction

### 1.1 Background

Polymer Composites have been in use in industry for more than 70 years. Their advantages compare to other materials such as high-performance and lightweight applications have attracted many industries such as aerospace, automobile, infrastructure, sports and marine to explore and increase their usage. Today's composites industry is faced with some very difficult challenges. There are numerous ways to manufacture fiber reinforced polymer composites ranging from hand lay-up in small series to fully automatic pressing of components to the automotive industry. As it is mentioned by Trochu et. al. [1], five major ways to manufacture structural fiber reinforced composites are presently in use: hand lay-up, autoclave, pultrusion, filament winding and Liquid Composite Molding (LCM). Parnas [2] has compared these processes with respect to manufacturing cost, performance and geometric complexity which are the key parameters to make the right choice between these processes. In this thesis two categories of manufacturing technologies, LCM and Out Of Autoclave (OOA) for structural long fiber reinforced composites, have been considered.

LCM manufacturing processes have progressed much in recent years. In case of large and complex geometries, LCM is the best alternative, often encountered in the automotive and aerospace sectors. This method actually represents a family of composite manufacturing processes that consists of injecting a liquid resin through a fibrous reinforcement. Several investigations were conducted to predict mold filling in LCM [3]-[8]. In LCM manufacturing, the reduction of liquid infusion time plays an important role on the overall cycle time and processing cost. In addition to predict the filling time, process simulation is the key to optimize the manufacturing process in respect to different aspects.. Also inadequate injection strategies will lead to create macro and micro-voids in the composite structure. Ruiz et. al. [9] has done an optimization algorithm which is used to calculate the injection flow rate that minimizes macro/micro void contents based on the analysis of fiber saturation during mold filling.

OOA manufacturing is an alternative to the traditional high pressure autoclave curing process for high quality composite materials, commonly used by the aerospace industry. OOA prepreg can be cured with only vacuum pressure and lower temperature [10]. Vacuum Bag Only (VBO) prepreps are a member of the family of OOA techniques for composite manufacturing in which composite laminates are produced from prepreps by vacuum-bag consolidation followed by curing in an oven [11]. The advantages of VBO compared to autoclave processing are lower capital investment, elimination of the need for costly nitrogen gas, greater energy efficiency and reduction of size constraints (larger parts) [12].

Considering the frequent application of LCM and OOA, the goal of this work is to develop a simulation tool to be applicable to the process modeling of these manufacturing technologies. To fulfill this goal, advanced theories of porous media are combined with the concept of finite strain hyperelasticity within a well-founded thermo-dynamical framework. In particular, a thermodynamically consistent constitutive setting is presented where a Neo-Hooke hyperelasticity formulation is embedded into the Theory of Porous Media (TPM). By focusing

on nonlinearities (due to large deformation of the preform) of the strongly coupled problem, the developed biphasic continuum mechanical model accounts for the relevant physical properties stemming from the porous microstructure, the moving and interacting incompressible fluid, and the directly coupled intrinsic hyperelasticity of the skeleton material itself. Finally, after the numerical treatment of the governing equations using finite element method, a large deformation 2-d problem was simulated to show the efficiency of the numerical implementation.

### 1.2 Composite Material

Composites are used in a large number of industrial applications ranging from high performance automotive and aerospace structures to common consumer products. Due to important properties such as high mechanical performance, high specific strength and stiffness, weight reduction resulting in energy saving and good resistance to corrosion; it was expected that the usage in industrial areas increase. These special advantages of composite materials have made them a good alternative for many metallic parts, especially in aerospace structures and transport sector.

Composite materials can be categorized by different perspectives; Figure 1 shows classification of composites based on reinforcing material, showing fiber reinforced composites (fibrous composites) in detail. Fiber Reinforced Plastics (FRP) have become increasingly important over the past 70 years, and are now the first choice for fabricating structures where low weight in combination with high strength and stiffness are required. Such materials are sometimes referred to as ‘high-performance’ composites, and would often be composed of carbon fibers and epoxy resin. ‘Density, stiffness (modulus) and strength are the properties that initially come to mind when thinking of FRP, and these would certainly be the design drivers for materials’ selection for transport applications such as aircraft, motor vehicles and trains’. [13]

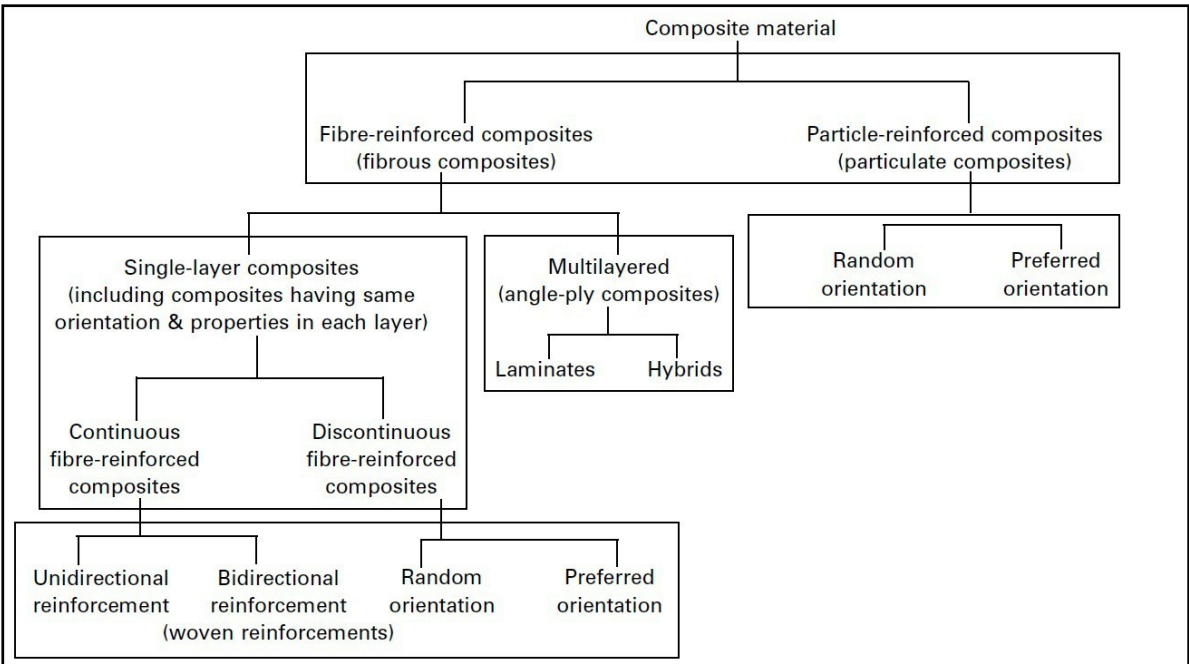


Figure 1: Classification of composite materials based on the type of reinforcing material structure [14]

### 1.3 Process Modeling in Composite Manufacturing

Manufacturing of composite materials is very different from metals. When producing metal parts, the properties of the virgin material and the finished part are fundamentally unchanged. In case of composites, the manufacturing process plays a key role. During composite processing, one makes not only the part of the desired shape, but also the material itself with specific properties. In addition, the quality of the composite material and the component fabricated depends on the manufacturing process since it is during the manufacturing process that the matrix material and the fiber reinforcement are combined and consolidated to form the composite. The practice of choosing an appropriate manufacturing method is based on the actual part size and geometry, the unit count, the selected components of the composite, i.e. the reinforcement and the matrix, and the cost.

Many new manufacturing techniques were invented and introduced during the last two decades, and some of them were incrementally improved to increase the yield of manufactured composite parts [15]. But before that, the manufacturability of a prototype was usually based on experience and ‘trial and error’ approaches because numerical simulation has not yet been applied to the development of control systems, which can correlate the main parameter values of the processes with the processing behavior and the final properties of the component [16]. Very little analysis of process physics and back-of-the-envelope calculations were done to approach a prototype development of a composite structure [15]. This way of manufacturing has proved to be expensive and composite industry has come under intense pressure to become cost effective and focus on cost avoidance in prototype development.

Composite manufacturing processes are generally grouped into two general classes: open mold and closed mold. Open mold are those processes in which the part is not inside the mold during the complete duration of the manufacturing process such as pultrusion or filament winding. In closed mold processes, the preform is placed in a mold, the mold is closed, and when it is reopened the part is fabricated. The focus of the current work is on the closed mold processes for continuous-fiber reinforced materials cf. Figure 2. For example, paper A focuses on the infusion problems such as Resin Transfer Molding (RTM) and Liquid Resin Infusion (LRI) while in paper B we model compression molding process of Evac prepregs.

We identify a set of elementary processes in the manufacturing operation, which can be well understood and modeled separately and then coupled together in later step. These processes are listed as

- Melting
- Wetting
- Preform and bundle deformation
- Drainage flow
- Void fraction prediction

The focus of this thesis has been on all but the melting process.

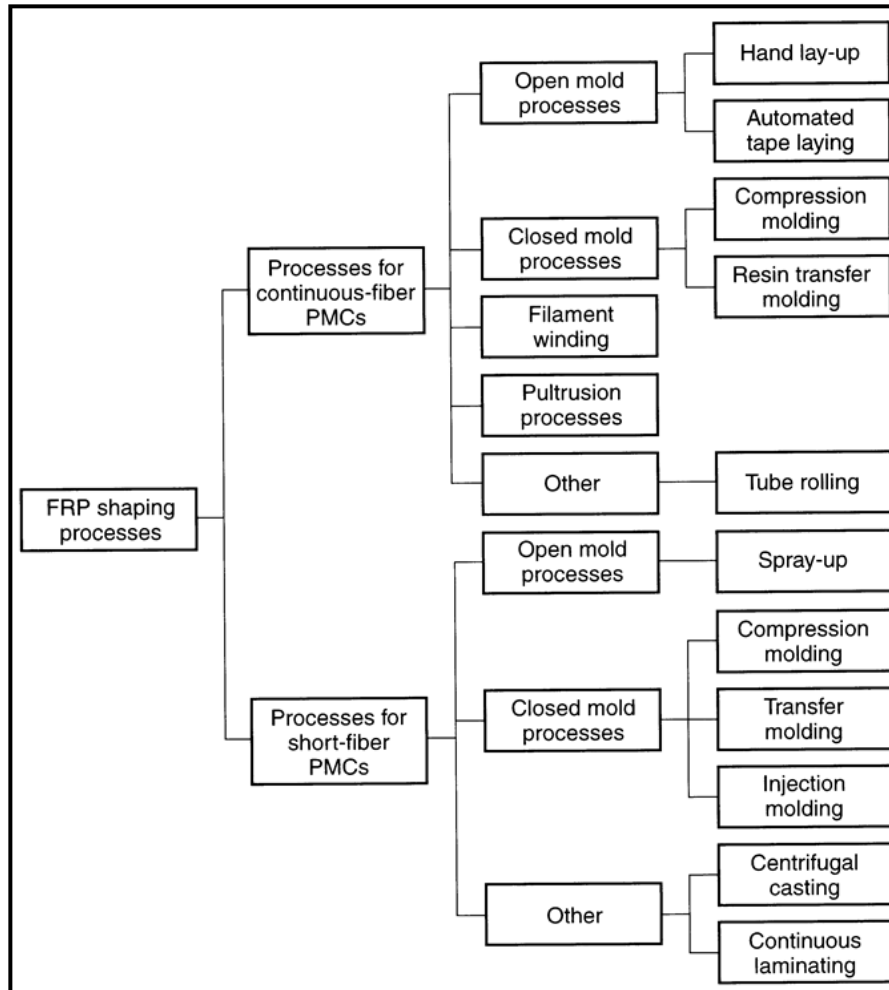


Figure 2: Structuring of FRP manufacturing processes [17]

#### 1.4 Computational Modeling of Porous Material

The area of multiphase materials modeling is a well-established and growing field in the mechanical scientific community. There has been a tremendous development in recent years including the conceptual theoretical core of multiphase materials modeling, the development of computational methodologies as well as experimental procedures. The applications concern modeling of engineered biomaterial [18], composites modeling [19]-[20], etc. Specific related issues concern modeling of solid-fluid interaction, compressible-incompressible fluids/solids including phenomena like consolidation, compaction, erosion, growth, wetting, drying etc. are well established and formulated [21]-[22].

Since the goal of this research is to develop a simulation tool, the essence of the computational methods is not negligible. ‘Computational mechanics is the discipline concerned with the use of computational methods to study phenomena governed by the principles of mechanics’. Here we use Finite Element Analysis (FEA) to simulate the process modeling in composite manufacturing. This is where we use theory of porous media as the back bone of the modeling. This theory will provide a framework for the modeling of a solid porous material with compressible and incompressible fluid phases. The constitutive relations who have been used here are restricted to hyper-elasticity and the ordinary Darcy model



describing the interaction between the constituents. The mathematical equations are then formulated which are suitable for digital computation. This step is basically where we derive the weak form of the equations with respect to domain and primary fields. The domain discretization along with primary field identifications are done based on the strongly coupled problem in hand to solve the governing equations of mass and momentum balance along respective constitutive equations where the Taylor-Hood element has been chosen for the simulation. Extensive description and formulation of the matter is exploited in paper A. Matlab is then used to solve the discretized equations using FEA. Computational procedures associated with the nonlinear response of the coupled two-phase material are also emphasized in our publications. The areas that are covered by this field concerning the physical interpretation of a particle are summarized below and well established in the papers for the particular cases. The following concepts of the theory of porous media are emphasized in the modeling of the manufacturing processes:

#### *The concept of two phase continuum*

We assume a fiber bed that is considered as a porous material. The pores are embedded into the solid fiber network; they are either partially filled by liquid resin or contains unfilled void spaces. As a result we have a porous solid which can be completely unsaturated, partially saturated or fully saturated. The constituents involved in the process can be assumed to be either compressible or incompressible.

#### *Darcian velocity and Terzaghi effective stress principle*

The mass and momentum balance are considered for quasi-static behavior of the mixture material formulated with respect to the contribution from different phases. Terzaghi effective stress 'felt' by continuum is considered where the total Cauchy stress is formulated in the momentum balance. Darcian velocity, also, defining the transport of liquid phase within the partially saturated continuum has been attributed to the mass balance of the mixture.

#### *Balance of energy and dissipation inequality for a two phase continuum*

We establish a combined balance of energy consideration for the mixture continuum which yields the change of internal energy of the mixture material. Furthermore, the dissipation inequality is formulated pertinent to the isothermal condition and is interpreted in terms of a few independent phenomenological mechanisms of the mixture material, which is the basis to develop the constitutive relations of the two-phase continuum.

#### *Constitutive relations*

As to the constitutive relations of the mixture material, we can mention the corresponding constitutive relations which have been developed in this thesis through the publications. The effective stress response as the result of the dissipation produced by solid phase material; and solid and fluid interaction guided by the interaction dissipation between the phases where we can embed the Darcy law to ensure positive dissipation are the two examples of constitutive relations for the mixture material. Based on the application of the framework other type of constitutive relation can be developed, c.f. to paper A & B.

## 2 Summary of Appended Papers

### *Paper A. Free surface flow and preform deformation in composites manufacturing based on porous media theory*

In this paper an infusion simulation tool is developed, applicable to a quite wide range of composites manufacturing technologies. The paper focuses on isothermal, infusion like manufacturing processes involving highly deformable preforms and a free surface resin flow. There are two major issues addressed at the modeling of the infusion processes: The first one is the highly deformable preform and its shape due to the interaction between external pressure loading and the intrinsic fluid pressure. The second issue concerns the migration of free surface due to resin infiltration into the fibrous preform. To resolve these both issues simultaneously, a compressible two-phase porous media formulation is put forward involving an additional liquid mass balance relationship as compared to the standard compressible porous media formulation. As a result a governing equation for saturation degree evolution is established, which is used to monitor the free surface problem directly in terms of the compressible continuum formulation traversing into incompressibility with increasing partial saturation degree. A staggered finite element based solution procedure is advocated for the total solution advancement, involving, on the one hand, the saturation dependent porous media formulation, and, on the other hand, the computation of the saturation degree. The proposed formulation has been implemented and numerical results are provided, showing the convergence of the staggered approach, and the assessment of the proposed approach against a 1D analytical model. In addition, the infusion of a “hat” beam is considered.

### *Paper B. Modeling of coupled dual-scale flow–deformation processes in composites manufacturing*

This paper is a part of the work towards a framework for holistic modeling of composites manufacturing. Here we focus our attention onto the particular problem of coupled dual-scale deformation–flow process such as the one arising in RTM, Vacuum Assisted Resin Infusion (VARI) and Vacuum Bag Only (VBO) prepregs. The formulation considers coupling effects between macro-scale preform processes and meso-scale ply processes as well as coupling effects between the solid and fluid phases. The framework comprises a nonlinear compressible fiber network saturated with incompressible fluid phase. Internal variables are introduced in terms of solid compressibility to describe the irreversible mesoscopic infiltration and reversible preform compaction processes. As a main result a coupled displacement–pressure, geometrically nonlinear, finite element simulation tool is developed. The paper is concluded with a numerical example, where a relaxation–compression test of a planar fluid filled VBO preform at globally un-drained and partly drained conditions is considered.

## 3 Conclusion

### 3.1 Remarks

In the present work we have developed a generic framework towards holistic modeling of composites manufacturing processes. Special applications, focused in the appended papers, are manufacturing processes of composite materials ranging from infusion type processes such as LRI and RTM, in paper A, to OOA processes such as Evac and VBO, in paper B.

In case of the LCM processes, we present a continuum model of a general two phase continuum formulation for infusion processes where we deal with the wetting, constitutive effective stress response of the fiber bed, flow front tracking and the coupling between the preform deformation and the free surface migration. A special porous media model has been developed involving the saturation degree concept, based on the additional liquid mass balance relationship. The model accounts for the non-saturated behavior typical for the transition region at the free surface between full- and non-saturation. The approach automatically monitors the free surface in smoothed fashion, whereby the monitoring of the resin front migration using e.g. level set control is completely avoided.

When dealing with OOA processes, we use similar framework to simulate this manufacturing family while the back-of-the-envelope physics has some differences. A special porous media formulation has been developed aimed for a dual-scale coupled flow-deformation process. In this framework, constitutive relations concerning four different mechanisms governing the process of press forming have been described to exploit constitutive effective stress response of the fiber bed, infiltration of resin into fiber plies, elastic packing response of the plies and Darcy's law governing the macroscopic interaction between the two phases.

The computational FE-treatment of the proposed models in conjunction with nonlinear kinematics is also numerically implemented and numerical examples are shown.

### **3.2 Future work**

Process modeling of manufacturing of composite materials is subjected to change every day by inventing new manufacturing techniques, new materials, new facilities, etc. So there will always be research issues to be considered with respect to physical phenomenon which are involved with the processes.

Further development through the current work that is already done in this thesis could be seen in different perspectives.

- Physical events happening through the process, melting, wetting, deformation, etc., should be studied as a chain of events to be able to capture their interactions.
- Optimization of the simulation routine can be further advanced by parallelization of the routine, designing a graphical interface.
- Formulating more mechanical properties for the different phases involve in the model, for example inelastic behavior of the fiber network, would widen the range of applications.
- Verification of the simulation tool through experimental method is also desirable.

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