# Book of Abstracts

12th International Conference on

# Flow Processes in Composite Materials

UNIVERSITY OF TWENTE.

12th International Conference on Flow Processes in Composite Materials

14 – 16 July 2014

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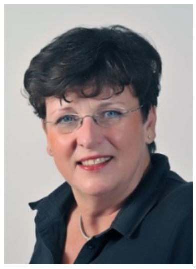

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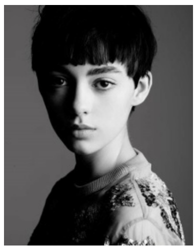

Ninouk Akkerman

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# PREFACE

The first international conference on Flow Processes in Composite Materials (FPCM) was organised in Uxbridge, UK. Prof. Cogswell[1] (guest editor of the special issue of Composites 1989, devoted to FPCM-1) cited the Collyer Committee on 'A Programme for the Wider Application of New and Improved Materials and Processes': *the evolution to full maturity requires not only excellent properties in the materials but also the ability to develop efficient and reliable processing technology by which to convert these substances into structures*. Cogswell concluded that *only when we finally establish the integrated optimization of material, process and design, will history accept the 'Age of Advanced Materials' as an established fact*. Twenty-five years later, this statement still applies to much of the research on composite materials processing. FPCM was organised five times in the UK, and subsequently travelled the world[2]: the conference was organised in Auckland (NZ), Delaware (USA), Douai (F), Montréal (CAN), Ascona (CH) and again Auckland (NZ). The twelfth episode of this series is organised again in Europe, at the University of Twente in Enschede, The Netherlands, from the 14$^{th}$ to 16$^{th}$ July 2014.

The University of Twente is proud to host this event, attended by renown composites experts from all over the globe. We aim to facilitate high level scientific discussion in a pleasant atmosphere at our friendly campus, located in an area rich with textile history and modern high tech materials related to this history. The conference programme has been carefully designed in a single session format, while allotting sufficient time for the poster sessions. The authors have been encouraged to submit their full papers for (another) special issue of Composites A: Applied Science and Manufacturing, to appear in 2015. Additionally, the authors could submit extended abstracts, made available on a separate memory stick. This book of abstracts is supplied to the conference delegates with ample space for making notes during the presentations. You will find some further information on the conference programme and how to get around in the area.

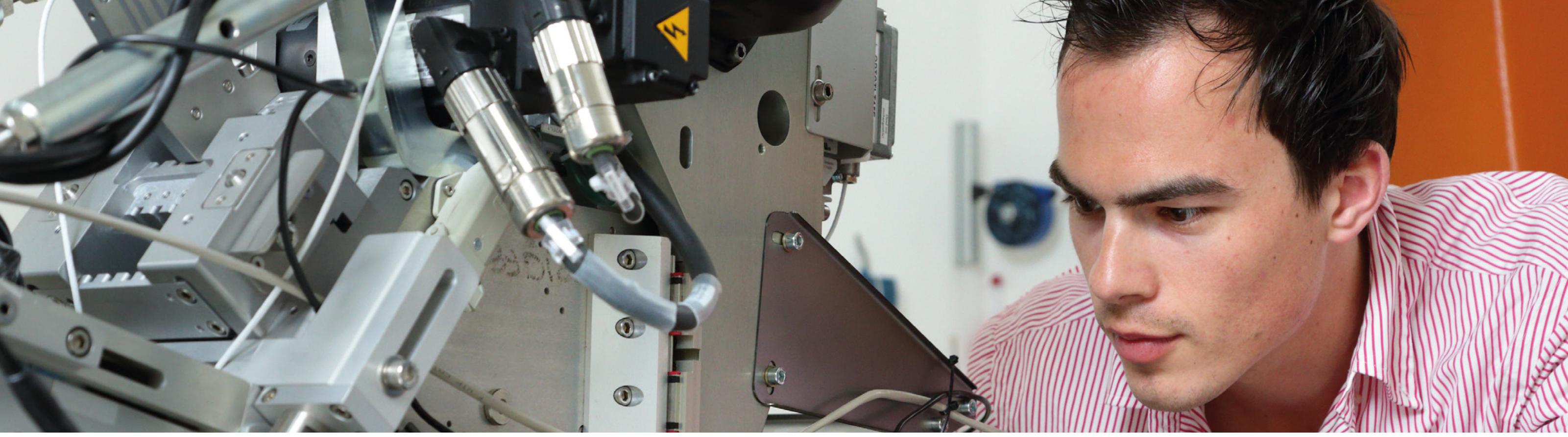
Finally a word of gratitude to all involved in making this conference happen. It was my pleasure to lead a very motivated local organising committee. The support of our secretaries Belinda Bruinink and Debbie Zimmerman and our student assistants made everything a lot easier. And of course: where is a conference without a scientific committee or without session chairs? Then the sponsors, who made it possible to maintain a moderate cost for all attendants. Many thanks to all involved: your help was very welcome indeed!

I wish all delegates a fruitful and pleasant time here in Twente. In the local dialect: goodgoan.

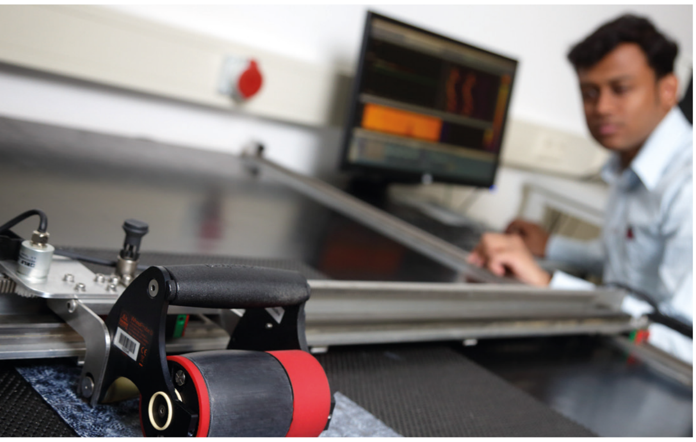
Remko Akkerman

chairman of FPCM-12.

[1] F.N. Cogswell, Flow processes in composite materials, Composites **20** (1989), p.2.
[2] For more information on previous FPCM conferences, please visit: http://www.tech.plym.ac.uk/sme/fpcm/











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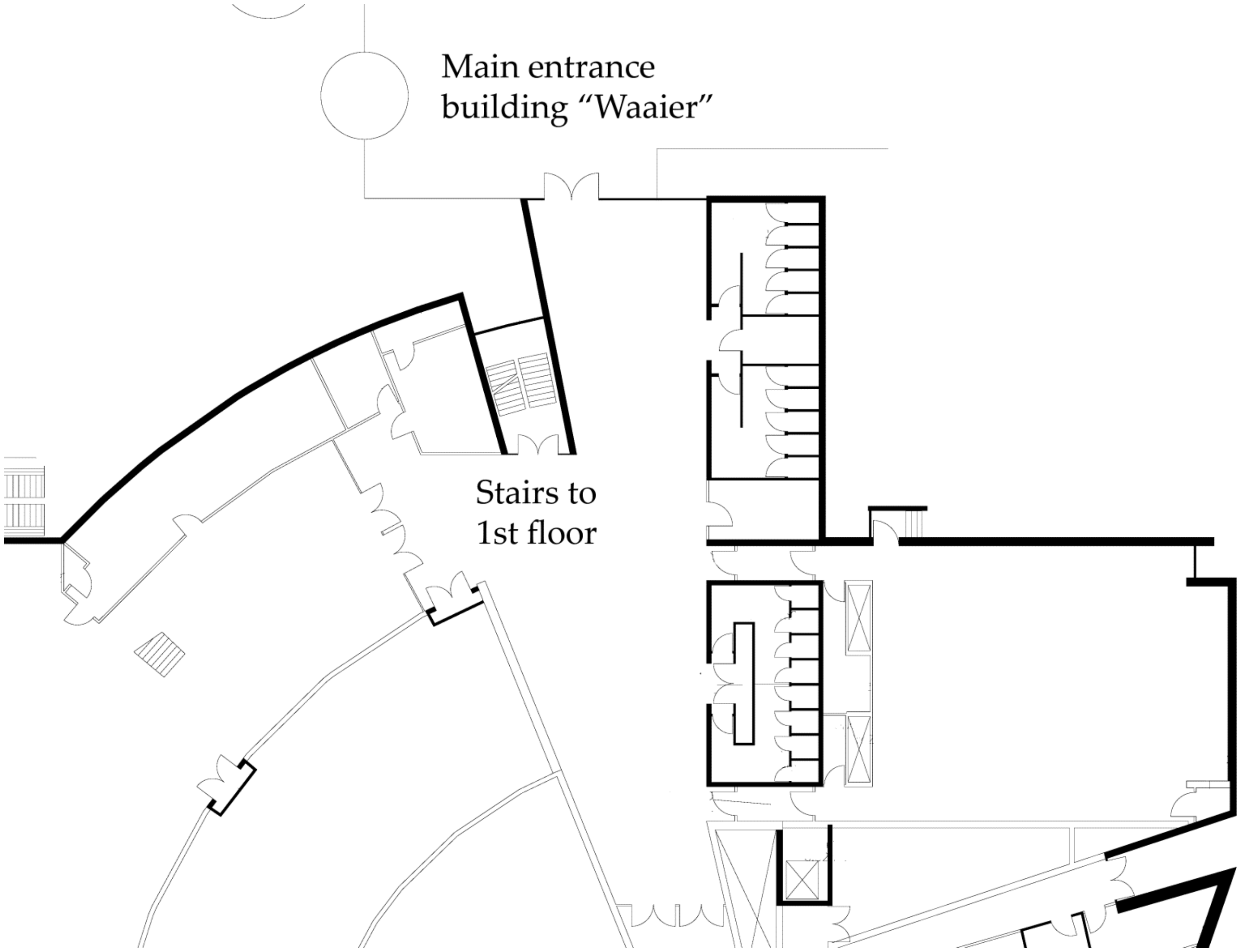
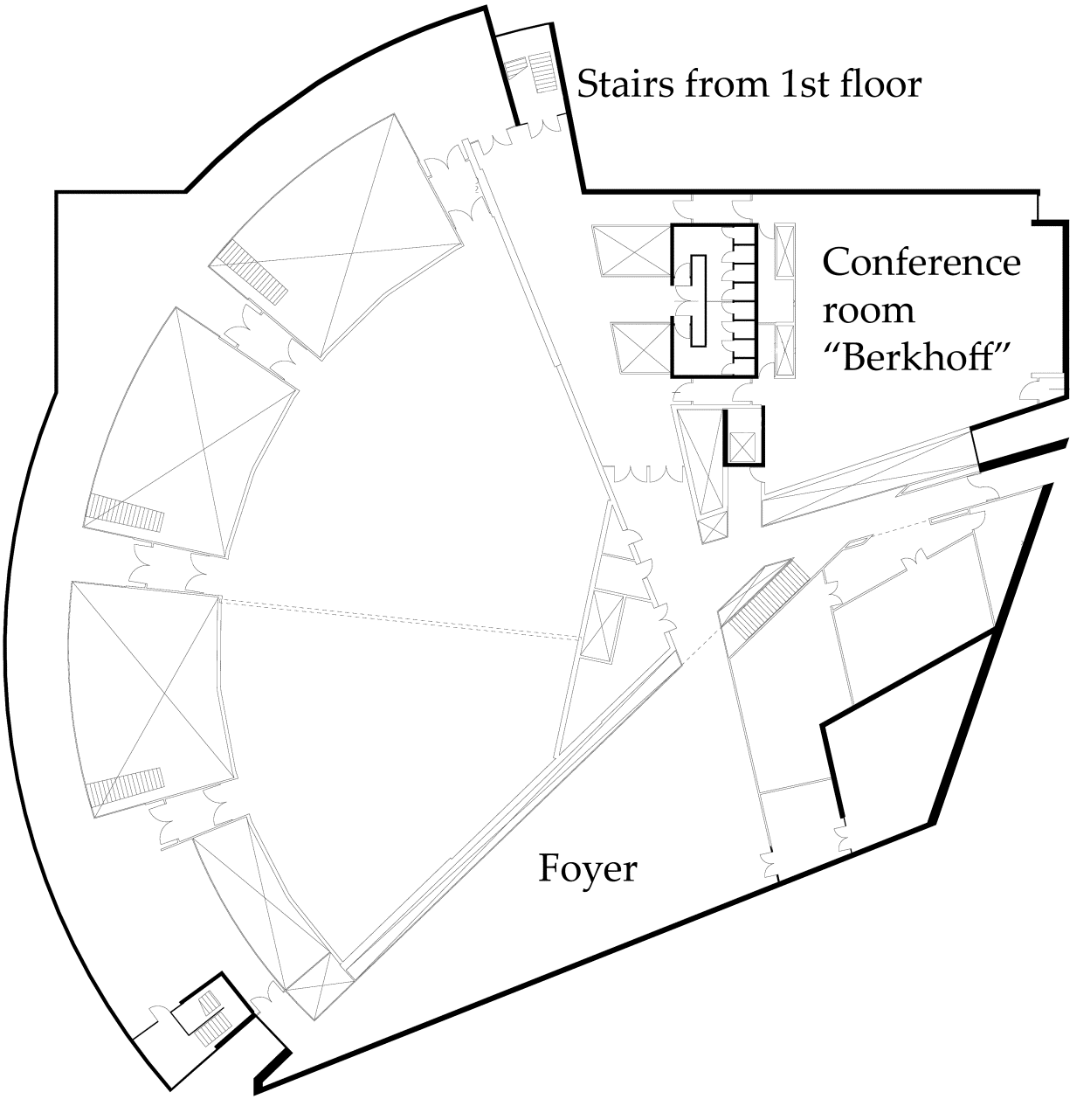
# CONFERENCE LOCATION "WAAIER"




Enter the "Waaier" building, located at the "O&O" square. Turn right in front of the reception desk of the building. Turn sharp right at the end of the short corridor to take the stairs to the first floor.

# CONFERENCE ROOM “BERKHOFF”




Go straight through the doors, the “Berkhoff” room is located on the left. You can find the registration desk approximately in front of the room.

Refreshment breaks will be in the foyer. The posters will also be displayed here.

# PROGRAM MONDAY 14 JULY 2014

| | | | |
|---|---|---|---|
| **8:00** | **Registration** | | |
| 8:10 | | | |
| 8:20 | | | |
| 8:30 | | | |
| 8:40 | **Opening** | | |
| 8:50 | | | |
| **9:00** | **Keynote I** | **Challenges in multifunctional composites manufacture and operation** | |
| 9:10 | | *Leif. Asp* | (Swerea SICOMP, Sweden) |
| 9:20 | | | |
| 9:30 | | | |
| 9:40 | Session I | Moulding defects in continuous fibre and randomly-oriented strands carbon/PEEK composites | |
| 9:50 | **Thermoplastic** | *Benoit Landry* | (Mc Gill University, Canada) |
| **10:00** | **Composites I** | Development of composite parts with RTM process based on new high fluidity thermoplastic polymers | |
| 10:10 | Chair: | *Gilles Orange* | (Solvay, France) |
| 10:20 | Remko Akkerman | Experimental investigation of the flow behavior of woven composite flakes in thermoplastic resin melt | |
| 10:30 | | *Mohammed Iqbal Abdul Rashid* | (University of Twente - TPRC, the Netherlands) |
| 10:40 | **Refreshment Break** | | |
| 10:50 | | | |
| **11:00** | | | |
| 11:10 | Session II<br>**Numerical Methods I** | Multi-scale modelling of combined deterministic and stochastic fabric non-uniformity for realistic resin injection simulation | |
| 11:20 | Chair: | *Andreas Endruweit* | (University of Nottingham, United Kingdom) |
| 11:30 | Suresh Advani | Capturing the variability of textile permeability from scanned images: A tool to automatically compute a textile permeability map | |
| 11:40 | | *Elinor Swery* | (University of Auckland, New Zealand) |
| 11:50 | | A Stochastic approach to modeling the effect of material variation in out-of-autoclave prepreg consolidation | |
| **12:00** | | *Rhena Helmus* | (University of München, Germany) |
| 12:10 | | Direct generation of finite element meshes of composites micro and mesostructure from 3D imaging: application to flow computation | |
| 12:20 | | *Luisa Silva* | (Mines ParisTech, France) |
| 12:30 | **Lunch Break** | | |
| 12:40 | | | |
| 12:50 | | | |
| **13:00** | | | |
| 13:10 | | | |
| 13:20 | | | |
| 13:30 | Session III | In situ flow visualization of void migration during out-of-autoclave thermoset prepreg processing | |
| 13:40 | **Void Dynamics** | *Thomas Cender* | (University of Delaware, United States) |
| 13:50 | Chair: Leif Asp | Volatile-Induced Voids in RTM Processing for Aerospace | |
| **14:00** | | *Mark Anders* | (University of Southern California, United States) |
| 14:10 | | Coupling the formation, movement, dispersion and effects of voids in resin infussion | |
| 14:20 | | *Mark Brandley* | (Brigham Young University, United States) |
| 14:30 | | Modeling hysteresis in liquid composite mold filling processes with void formation | |
| 14:40 | | *Antonio García* | (Universitat Politecnica de Valencia, Spain) |
| 14:50 | **Poster Session and Refreshment Break** | | |
| **15:00** | | | |
| 15:10 | | | |
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| 15:40 | | | |
| 15:50 | Session IV<br>**Characterisation** | Efficient method to characterize textile permeability as a function of fiber volume content with a single UD injection experiment | |
| **16:00** | **Methods** | *Claudio di Fratta* | (ETH Zurich, Zwitserland) |
| 16:10 | Chair: | Influence of preforming technology on het out-of-plane impregnation behavior of textiles | |
| 16:20 | Christophe Binetruy | *David Becker* | (Institut für Verbundwerkstoffe GmbH, Germany) |
| 16:30 | | Rigid tooling for optical 3D wetting permeability measurements | |
| 16:40 | | *Andrew George* | (Brigham Young University, United States) |
| 16:50 | | Permeability Benchmark discussion | |
| **17:00** | | *Francois Trochu* | (Ecole Polytechnique Montreal, Canada) |
| 17:10 | | | |
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| 17:50 | | | |
| **18:00** | **Reception at City Hall Enschede** | | |

# PROGRAM TUESDAY 15 JULY 2014

| | | |
|---|---|---|
| **8:00** | | |
| 8:10 | | |
| 8:20 | | |
| 8:30 | **Keynote II** | **Vacuum Assisted Process® – Technology for large Aerostructure Components** |
| 8:40 | | *Mathias Friedrich* (Premium Aerotec, Germany) |
| 8:50 | | |
| **9:00** | | |
| 9:10 | Session V | A lubrication approach to friction in forming processes with thermoplastic UD composites |
| 9:20 | **Thermoplastic** | *Uli Sachs* (University of Twente - TPRC, The Netherlands) |
| 9:30 | **Composites II** | Pultrusion process for continuous fiber reinforced thermoplastic composites |
| 9:40 | Chair: | *Asami Nakai* (Gifu University, Japan) |
| 9:50 | Pascal Hubert | Modeling of unsaturated flow in woven fibers during direct injection-pultrusion process of thermoplastic composites |
| **10:00** | | *Arthur Babeau* (Ecole Centrale de Nantes, France) |
| 10:10 | **Poster Session and Refreshment Break** | |
| 10:20 | | |
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| 10:40 | | |
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| **11:00** | | |
| 11:10 | Session VI | Numerical prediction of in-plane permeability for woven fabric with manufacture induced deformation |
| 11:20 | **Numerical Methods** | *Xuesen Zeng* (University of Nottingham, United Kingdom) |
| 11:30 | **II** | An adaptive monolithic Finite Element approach for the numerical simulation of compression Resin Transfer Molding processes |
| 11:40 | Chair: Alfred Loos | *Jerome Claracq* (DOW Benelux BV, The Netherlands) |
| 11:50 | | Eulerian approach for computational fluid-solid mechanics with capillarity issues for resin infusion based process |
| **12:00** | | *Pierre-Jacuqes Liotier* (Hexcel Reinforcements, France) |
| 12:10 | | Direct numerical orientation of fiber in shear flow for complex fluids |
| 12:20 | | *Patrice Laure* (Laboratoire J.A. Dieudonné, France) |
| 12:30 | **Lunch Break** | |
| 12:40 | | |
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| **13:00** | | |
| 13:10 | | |
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| 13:30 | Session VII<br>**Particle Dynamics** | Processing and characterization of multi-scale composites manufactured by out-of-autoclave Resin Film Infusion |
| 13:40 | Chair: | *Pascal Hubert* (McGill University Montreal, Canada) |
| 13:50 | John Summerscales | Packing and permeability properties of E-glass fibre reinforcements functionalised with capsules for self-healing applications |
| **14:00** | | *Erica Manfredi* (EPFL Lausanne, Zwitserland) |
| 14:10 | | Combining process simulation and sensing for optimised composites manufacturing |
| 14:20 | | *Nikos Pantelelis* (Synthesites Innovative Technologies, Greece) |
| 14:30 | **Refreshment Break** | |
| 14:40 | | |
| 14:50 | | |
| **15:00** | Session VIII | Coupling between heat transfer and saturation: experimental investigation |
| 15:10 | **Process monitoring &** | *Vincent Sobotka* (Université de Nantes, France) |
| 15:20 | **Control** | Liquid Composite Moulding flow front characterization by Micro-CT |
| 15:30 | Chair: | *Matthew Streeter* (University of Southampton, United Kingdom) |
| 15:40 | Peter Mitschang | Monitoring non-isothermal polymerization and crystallization of cyclic butylene terephthalate composites manufactured by RTM |
| 15:50 | | *Inigo Ortiz de Mendibil* (Mondragon Unibertsitatea, Spain) |
| **16:00** | | Increasing the robustness and reliability of cfrp production processes through systematic analysis and process monitoring |
| 16:10 | | *Christopher Buchmann* (EADS Innovation Works, Germany) |
| 16:20 | **Refreshment Break** | |
| 16:30 | | |
| 16:40 | | |
| 16:50 | Session IX | Development of an innovative preforming process for the high-volume automotive sector |
| **17:00** | **Innovative Processes** | *Maximilian Marquart* (BMW AG, Germany) |
| 17:10 | Chair: | Tool vibrations for the advancement of the vacuum Infusion process |
| 17:20 | Paolo Ermanni | *Nikos Pantalelis* (Synthesites Innovative Technologies, Greece) |
| 17:30 | | In-mould gel-coating with a separator layer |
| 17:40 | | *John Summerscales* (Plymouth University, United Kingdom) |
| 17:50 | | Effect of surface treatment for continuous fibers on impregnation and mechanical properties of thermoplastic composites |
| **18:00** | | *Akio Ohtani* (Gifu University, Japan) |
| | **Conference Dinner at Bloemenbeek** | |

# PROGRAM WEDNESDAY 16 JULY 2014

| | | | |
|---|---|---|---|
| **8:00** | | | |
| 8:10 | | | |
| 8:20 | **Keynote III** | | |
| 8:30 | | *Arjan Koorevaar* | (Polyworx, The Netherlands) |
| 8:40 | | | |
| 8:50 | | | |
| **9:00** | Session X | Experimental analysis of flow behavior in the flax fiber reinforcement with double scale porosity | |
| 9:10 | **Natural Fibre Composites** | *Van Hau Nguyen* | (Ecole nationale supérieure des Mines de Douai, France) |
| 9:20 | Chair: | Capillary effects on flax fibres reinforcements; comparison of chemical and morphological effects on the local wetting dynamics | |
| 9:30 | Richard Loendersloot | *Monica Pucci* | (Ecole des Mines de Saint-Etienne, France) |
| 9:40 | | Shear viscosity data of natural fibre compounds for the modeling of polymer processes through reverse engineering | |
| 9:50 | | *F. Desplentere* | (KU Leuven, Belgium) |
| **10:00** | | Mold filling simulation in rtm processing of natural fiber composite materials | |
| 10:10 | | *G. Francucci* | (National University of Mar del Plata, Argentina) |
| 10:20 | **Refreshment Break** | | |
| 10:30 | | | |
| 10:40 | | | |
| 10:50 | Session XI<br>**Material Modelling** | Design of a quasi-unidirectional fabric for RTM process with high fluidity thermoplastic: longitudinal permeability and microstructure | |
| **11:00** | Chair: | *Guillaume Cazaux* | (University of Le Havre, UMR CNRS, France) |
| 11:10 | Veronique Michaud | A micromechanical model to simulate capillary flows in dual scale porous media | |
| 11:20 | | *Claudia Thurnher* | (Ecole Polytechnique Montreal, Canada) |
| 11:30 | | High temperature VARTM using LaRC-PETI-9 Polyimide Resin | |
| 11:40 | | *Alfred Loos* | (Michigan State University, United states) |
| 11:50 | | Modeling and validation of through thickness flows in fully wetted textiles during consolidation | |
| **12:00** | | *Mario Danzi* | (ETH Zürich, Zwitserland) |
| 12:10 | | Analysis of multi-scale effects on the permeability of fabrics for liquid composite molding | |
| 12:20 | | *Luca Bergamasco* | (Instituto Tecnológico de Aragón, Spain) |
| 12:30 | **Lunch Break** | | |
| 12:40 | | | |
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| **13:00** | | | |
| 13:10 | | | |
| 13:20 | | | |
| 13:30 | Session XII | Air evacuation in consolidation modeling of Out of Autoclave prepregs | |
| 13:40 | **Numerical Methods** | *Theodosia Kourkoutsaki* | (University of München, Germany) |
| 13:50 | **III** | Process modeling of composite materials – A holistic and generic simulation tool using poromechanics | |
| **14:00** | Chair: | *Mohammad Rouhi* | (Swerea SICOMP, Sweden) |
| 14:10 | Francois Trochu | An efficient scheme to model resin flow in a deformable porous media using RTM infusion simulation | |
| 14:20 | | *Suresh Advani* | (University of Delaware, United States) |
| 14:30 | | Impregnation of composites at the unit cell level | |
| 14:40 | | Edwin Lamers | (Reden BV, The Netherlands) |
| 14:50 | **Closure at TPRC** | | |
| **15:00** | | | |
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# Abstracts of Presentations

# CHALLENGES IN MULTIFUNCTIONAL COMPOSITES MANUFACTURE AND OPERATION

Leif Asp

*Swerea SICOMP, Sweden*

The presentation addresses structural power composites – their design, manufacture and performance. Focus is given on structural battery composite materials, employing carbon fibres as combined electrodes and reinforcement of the material and a solid polymer electrolyte matrix material. The processing of these materials face a number of new challenges, as for example moisture free ambient conditions, that will be discussed. The multifunctional performance relies not only on high quality in the processing of the materials, but also on material selection and architecture. Particular focus will be given to the means to achieve efficient L-ion migration between the electrodes in the structural battery.

# NOTES

# MOULDING DEFECTS IN CONTINUOUS FIBRE AND RANDOMLY-ORIENTED STRANDS CARBON/PEEK COMPOSITES

Benoit Landry*, Pascal Hubert

*McGill University, Canada*
*Corresponding author's email: benoit.landry3@mail.mcgill.ca*

**Keywords:** thermoplastics, discontinuous fibre, voids, damage tolerance

The paper will present an experimental investigation of the effect of void content and loss of pressure during cooling on the mechanical properties of Randomly-Oriented Strands (ROS) carbon/PEEK composites, a bulk moulding compound type of material made of strands of unidirectional pre-impregnated tape. This new type of material has great formability compared to continuous fibre composites and is intended to be employed to manufacture small intricate compression moulded components having features such as varying wall thickness, tight radii, reinforcing ribs, mould-in holes, etc. ROS composites parts are processed by randomly placing material in a compression mould, applying heat in order to melt the material and pressure to force the material to flow and fill the mould cavity. During this process, the initial voids between the strands at room temperature are filled by the flow of material and the crushing of the air pockets under pressure at melt temperature. With increasing part complexity, the processing pressure to completely fill the mould cavity will rapidly rise, making it more and more difficult to manufacture a void-free component. It is thus important to quantify effect of voids on the mechanical performance of ROS composites and determine the maximum void content that the composite can tolerate without compromising its mechanical properties.

In this study, two common sources of voids during manufacturing of ROS composites will be investigated. The first one is due to insufficient moulding pressure and/or dwell time at the pro-cessing temperature, which will lead to an inadequately filled cavity, thus voids in the part. Preliminary micro-computed tomography (micro-CT) results have shown very high void content in the complex regions of ROS parts. To simulate this type of voids, several flat panels will be manufactured at different levels of void content. This will be achieved by controlling the displacement of the press platens to control the final part thickness. Keeping the final thickness constant for all panels, the final void content will be controlled by varying the amount of material initially put in the mould cavity. The second source of voids is caused by non-uniform part cooling, where localized shrinkage and uneven modulus development of the material will create a pressure gradient on the part. Coupled with insufficient compaction compensation during cooling, it will lead to a loss of contact between the mould and the material, where void growth might occur, especially near the surface. This manufacturing defect will be recreated by applying a high-pressure cycle to flat panels, followed by the release of the pressure at different temperatures during the cooling process. A correlation will be made between the temperature at pressure loss, void content and resulting mechanical properties. In all cases, the void content will be measured using micro-computed tomography, combined with cross-sectional micrographs further understand their morphology. Finally, the material's tolerance to voids will be quantified by comparing their tensile, compressive and flexural properties to void free laminates.

# NOTES

# DEVELOPMENT OF COMPOSITE PARTS WITH RTM PROCESS BASED ON NEW HIGH FLUIDITY THERMOPLASTIC POLYMERS

Gilles Orange*, Emeline Bessard, Joel Breard, Laurent Bizet, Jean Luc Bailleul, Christophe Binetruy, Philippe Boisse, Moussa Gomina

*Solvay, Hutchinson, LOMC, CNRS - Universit é Le Havre, LTN, CNRS - Universit é Nantes, GeM, Ecole Centrale Nantes, LaMCOs, INSA Lyon, CRISMA T, ENSICA EN, France*
**Corresponding author's email: gilles.orange@solvay.com*

**Keywords**: thermoplastic composites, polyamide, RTM, glass fibers & fabrics, preform viscosity impregnation, crystallization

Today's development of semi-structural and structural composite parts in automotive industry is limited by the total cost of ownership as well as low production rate. This inability to produce parts of complex geometry at controlled cost prevents the use of thermoplastic composite materials for applications in medium to large series, despite the major advantages of these materials as their low environmental impact (no solvents /no VOCs, and recyclability) and their good behaviour in crash stress (intrinsic ductility). A fast and complete impregnation of textile reinforcement by the melt thermoplastic resin is one of the key issues: it is controlled by the reinforcement structure (fibrous preform) and the resin characteristics as wettability and viscosity. Among the different manufacturing processes of composite structures, the impregnation at low pressure of a dry preform placed in a mould (Liquid Composite Molding) presents a major interest in the production of parts with complex geometry (non-developable surfaces) with the possibility of integrated functions. A R&D Consortium ('Tapas- LCM') has been built up between industrial and academic partners to develop a new process based on LCM and new thermoplastic polymers.

New thermoplastic polymers based on polyamide chemistry (aliphatic and semi- aromatic) with low viscosity have been specially developed. A specific lab RTM unit has been designed : melt polymer injection in a instrumented hot mould. Several difficulties have to be overcome to develop such new processes : thermal transfer and thermal cycle, wettability and impregnation at high rate of a given fibrous structure (deformable perform, with variable permeability), control of the in-situ polymer crystallization and induced residual stresses in final composite parts.

First results show the technical feasability of RTM process based on high fluidity thermoplastic polymers with a complete impregnation (void content < 1%) at low injection pressure ( □P < 1.5 M
50% and 60% vol., leading to high performances composites. Optimization has to be done on preform permeability and polymer characteristics (rheology, and physico-chemistry) to improve the process cycle time.

# NOTES

# EXPERIMENTAL INVESTIGATION OF THE FLOW BEHAVIOR OF WOVEN COMPOSITE FLAKES IN THERMOPLASTIC RESIN MELT

Mohammed Iqbal Abdul Rasheed*, Bert Rietman, Hendrikus A. Visser, Remko Akkerman

*ThermoPlastic Composites Research Center, University of Twente, The Netherlands*
**Corresponding author's email: m.i.abdulrasheed@utwente.nl*

**Keywords**: thermoplastic, composite, discontinuous, flake, reinforcement, compression, flow, visualization

Discontinuous thermoplastic composites are gaining an increasing attention due to its relative ease of manufacturing of complex shapes, compared to the continuously reinforced composites. The discontinuous nature gives increased toughness, but reduces the strength of the composite considerably. Apart from the constituent material properties, the strength of such material is influenced by the meso-structure of the discontinuous reinforcements formed during the compression molding process. An unwanted resin rich region or a resin deprived dry spot is a potential cause for premature failure initiation. Therefore, information on the flow behavior of these flake reinforcements in the resin melt during molding is necessary in order to describe the material behavior of the compression molded parts. Moreover, the shear forces generated by this highly viscous polymer melt during the flow can cause shear deformation of woven flake reinforcements in addition to the dynamic interaction between the flakes. Usually, the melt conditions of fiber reinforced thermoplastics are assumed to be incompressible viscid or viscoelastic. During compression molding both shear and extensional flow is likely to be involved near the walls and the center of the mold respectively.

The behavior of unidirectional chopped tapes under squeeze flow conditions is investigated by research groups around the world. In this study, the flow of woven composite flakes in a thermoplastic resin melt under compression is characterized experimentally. Tracing elements in the form of the flakes are used in the input material to detect the motion of the flakes in the molded part. Unlike the use of a preform of fiber reinforced composite in the squeeze flow experiment, the experiment conducted in this study is based on the flow of discontinuous elements directly during the molding process. A 60 x 60 mm mold is filled with a measured amount of carbon/PPS flakes with no additional resin. The mold is closed at a specified rate at an elevated temperature. The force during the experiment is maintained constant and the relative distance of the mold surfaces is monitored. A parametric analysis of the variables viz. force, rate of closing, filling pattern and flake size is performed to arrive at a suitable process description. A comparison is also made with a theoretical model for squeeze flow.Since the process involves high temperatures, online monitoring of the flow is not possible except for the post-molding analysis of the position of the tracers. Therefore, a visualization experiment at room temperature is set up to gain an insight on the flow of material with the conditions similar to the melt conditions inside the mold. This experiment is carried out with a translucent fluid whose viscosity at room temperature is close to the melt viscosity of the thermoplastic polymer (PPS) used. Flakes of isotropic materials are used in this analogous experiment to visualize the flow when compressed between two glass plates. Compression experiments with the actual composite flakes are compared against the analogous experiment. The effect of formation of dry spots and incomplete filling of the mold observed in the compression experiments are discussed.

# NOTES

# MULTI-SCALE MODELLING OF COMBINED DETERMINISTIC AND STOCHASTIC FABRIC NON-UNIFORMITY FOR REALISTIC RESIN INJECTION SIMULATION

Andreas Endruweit*, Xuesen Zeng, Andrew C. Long

*University of Nottingham, United Kingdom*
**Corresponding author's email: andreas.endruweit@nottingham.ac.uk*

**Keywords**: textile fabric, stochastic properties, drape, process simulation, permeability

In Liquid Composites Moulding (LCM) processes, the impregnation of fibrous reinforcements with liquid resin systems is frequently described by the model of a viscous liquid flowing through a porous medium, characterised by its porosity and permeability. Prediction of resin injection scenarios is relatively straightforward if porosity and permeability are uniform. However, for the most common type of reinforcement, bi-directional fabrics, these properties tend to show some degree of non-uniformity. Deterministic non-uniformity is related to the effect of drape, i.e. (localised) shear when the reinforcement is formed to a doubly-curved surface.

Stochastic non-uniformity is related to material-inherent yarn mobility which makes a fabric susceptible to involuntary local deformation. Reinforcement non-uniformity results in irregular mould filling patterns and variable fill times, which makes the outcome of resin injections in LCM-processing of actual components hard to predict. In this study, resin injection into a bi-directional fabric formed to a complex shape is modelled considering deterministic and stochastic non-uniformity in fabric properties. In addition to material-inherent fabric non-uniformity, which is modelled as in-plane yarn waviness, the uncertainty in initial conditions for the forming process is considered here. To mimic the uncertainty in placing a dry reinforcement in a tool as start for the following deterministic forming process, drape simulation was randomised in terms of start point and yarn start orientations, which determine yarn paths and local fabric shear angles. Local fabric permeabilities are calculated from yarn spacing distributions considering the dual-scale structure of fabrics.

For demonstration of the proposed approach, resin injection into a fabric formed to a complex geometry was simulated considering the randomised forming process, the stochastic yarn arrangement in the fabric and, to account for the dual-scale structure of fabrics, the stochastic arrangement of filaments within yarns. It was observed that variability in fabric properties and the forming process affects flow front shapes and results in an increase in mould fill time. It is concluded that random effects should be considered in simulations, e.g. using a Monte-Carlo approach, to allow prediction of the most probable scenarios and the range of possible outcomes.

# NOTES

# CAPTURING THE VARIABILITY OF TEXTILE PERMEABILITY FROM SCANNED IMAGES: A TOOL TO AUTOMATICALLY COMPUTE A TEXTILE PERMEABILITY MAP

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**Keywords**: permeability, textile modelling, computational simulation, liquid composite moulding

Liquid Composite Moulding (LCM) process simulations are increasingly used as process design tools to select optimal manufacturing parameters for fibre reinforced polymer (FRP) composite materials. Accurate permeability data of reinforcing textiles is essential input for these simulations. It is desirable to capture the textile's permeability as well as its spatial variation in order to improve the accuracy of the process simulation.

An automated tool has been developed and is presented, generating permeability predictions of unit cells using textile modelling techniques. This tool incorporates the functionality of TexGen (developed at the University of Nottingham) to generate unit cell geometries based on simple scanned images of the textile. Compaction simulations are initially applied to the unit cells, reflecting the change of geometry due to the textile compaction. Voxel meshes representing the volume of resin around the compacted geometries are then exported. The voxel meshes are then automatically cleaned, deleting any floating elements, and the boundary regions defined based on the unit cell size.

By executing flow simulations on these meshes, the permeability characteristics of a large range of unit cells may be obtained. This enables the creation of a database of predicted permeability values for varying unit cell geometric parameters. The complete process is executed within the MATLAB environment, allowing the full automation of the process through the use of scripting functions.

A novel scanning set up has been incorporated into the existing 2D in-plane permeability facility at the Centre for Advanced Composite Materials. This provides high resolution scans of the reinforcing textiles prior to injection without the risk of further handling deformations. These scans are then used to create equivalent geometric models of the textile tested for direct comparisons.

Using this set up along with the permeability prediction tool, the permeability maps of preforms comprised of single layers of woven textiles were generated, capturing the textile variability and its influence on the permeability properties. The textile geometries were discretised into unit cells of varying geometries, reflecting the variability observed. The permeability maps were then generated from the corresponding unit cell permeability results. These permeability maps were used within SimLCM (an LCM processes simulation tool developed at the University of Auckland) to execute the process simulations and compute the predicted flow front.

The predicted flow fronts were compared with the observed flow front obtained by conducting the permeability experiments on the textiles examined. By scanning the textile directly within the permeability testing facility, a permeability map is able to be generated for the textile in its final form, enabling direct comparison of the predicted and the observed flow front during injection. A review of the usability of such a process to obtain the permeability map of reinforcing textiles is presented along with a summary of the computation times involved in each of the steps.

# NOTES

# A STOCHASTIC APPROACH TO MODELING THE EFFECT OF MATERIAL VARIATION IN OUT-OF-AUTOCLAVE PREPREG CONSOLIDATION

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**Keywords**: out-of-autoclave, consolidation, stochastic approach, variability

The increasing demand for composite materials as well as the request for sustainability pioneered the design of Out–of-Autoclave (OoA) prepreg material. In contrast to traditional autoclave prepregs, OoA material can be processed in a conventional oven with a vacuum bag only. The lack of pressure makes part fabrication vulnerable to voids which ultimately determine the quality of the laminate. OoA consolidation involves fiber bed compaction, air evacuation through the dry fibre tows of a partially saturated microstructure, and subsequent resin flow into these dry areas. The latter decisively influences the achievement of a void free structure and is determined by multiple factors. In order to describe the material properties and condition at the end of the consolidation process, a realistic representation of the complete process is necessary.

When the spatial variance of material parameters is neglected, the consolidation process would proceed equally throughout the part leading to the same material properties across the whole laminate. This is not the case in reality, evident on CT scans e.g. [1]. Within this context, the present study describes the consolidation process of OoA prepregs with the help of a representative unit cell using a stochastic approach. A fundamental problem in modeling flow processes in OoA consolidation arises by locally specific conditions determining the flow, e.g. variation in fibre volume fraction, initial resin distribution and material constitution leading to different flow behaviour across the laminate. These small scale heterogeneities can be determined by experiments punctually only while a parameterization of the effect on final void content in the laminate is hard to facilitate. The consideration of spatial variations in material configuration has therefore to be done via an "effective" parameter which is calibrated in a stochastic manner based on Monte Carlo Simulation. In this study an analysis of initial resin distribution is conducted with the help of CT scans which is then used for the calibration of the parameters necessary for the consolidation model.

Altogether, the study develops an approach for describing stochastic variations within the prepreg material and their effect on the phenomena taking place during OoA processing. It establishes a simulation workbench to virtually investigate the interaction and progression of these phenomena which define the final part's quality. Ultimately, the model provides a basis for adding further complexity, such as fibre bed variation, to the existing analysis tools.

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## NOTES

# DIRECT GENERATION OF FINITE ELEMENT MESHES OF COMPOSITES MICRO AND MESOSTRUCTURE FROM 3D IMAGING: APPLICATION TO FLOW COMPUTATION

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Nowadays, to accurately simulate evolution of the behavior of a composite at the mesoscopic (yarn) or microscopic (fiber) scales, the finite element method appears as a powerful tool, with the increase on the computational power through the use of grids or cloud computing. In order to be quantitatively pertinent, the numerical descriptions of the meso or microstructure must be well defined and in-situ 3D imaging techniques, like X-Ray tomography (micro or nano) are very interesting, since they access the heterogeneity of the different phases with a definition and quality that can be important. To pass from imaging to finite element domains, we need to have performing mesh generation algorithms, preferably directly from the real data (like the 3D images). In the literature, generation of finite element meshes from images is the most often treated using image analysis tools like ImageJ, coupled with mesh construction ones (for example, Amira). They are based on a three-step procedure: segmentation, for the identification of the different phases (polymer, fibres, eventually voids) in the image; construction of a surface mesh for each phase, representing its boundary; construction of one or several volume meshes on which the specific properties of each phase can be defined.

In this paper, we propose an alternative way to build directly finite element representation of composite meso and microstructures using an "image immersion" method, by skipping the Marching Cubes' step. Firstly, a coarse mesh is considered and the image voxel values (color or grey scale) are mapped in this mesh by a direct interpolation, providing a topographic distance field distribution on the mesh. Hence, in regions where there is a strong difference on the topographic function, the mesh will become finer in the sense of this difference. Then, an appropriate error estimator built from this distance is used to compute a metrics field that our topological mesher will consider to adapt the mesh. Finally, we define a topographic's distance isovalue for each interface contour and we build, through a coupled reinitialization - automatic anisotropic mesh adaptation algorithm, the distribution of a phase function for each existing phase. Meshes obtained using these techniques are well adapted for monolithic based methods (one mesh containing all the phases, each represented by an implicit - phase – function, like in classical diffuse interface methods). Mesh adaptation provides nodal enrichment near these interfaces, which will allow results to converge to a "sharp-interface" solution.

Computations on such meshes will illustrate the relevance of our methodology. At the fiber scale, images containing thousands of fibers are analyzed and flow around these fibers will be calculated using a mixed finite element method, obtained through discretization of the Stokes equations and by considering rigid body motion for the fibers. At the yarn scale, Stokes-Brinkman equations are also solved through a mixed finite element method, but by modifying its stabilization. Applications include, for example, permeability determination.

# NOTES

# IN SITU FLOW VISUALIZATION OF VOID MIGRATION DURING OUT-OF-AUTOCLAVE THERMOSET PREPREG PROCESSING

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**Keywords**: voids, resin, two-phase flow, fiber tow saturation, flow visualization

The mitigation of voids during composites processing remains an expensive composites manufacturing issue, as the presence of voids in composite parts can lead to degraded mechanical properties. The development of partially impregnated Out-of-Autoclave (OOA) thermoset prepregs has sought to reduce costs while achieving high quality; however, understanding of void migration and reduction during OOA processing remains challenging. The following work presents a model experiment that investigates how trapped voids in the OOA prepreg are transported during processing. The experiment utilizes a characteristic partially impregnated prepreg with lodged voids that is subjected to a pressure gradient at the processing temperature, for removal through porous pathways within the prepreg. The experiment utilizes an in situ flow visualization technique to capture the two-phase resin and void flow through the prepreg. Void velocity and size with respect to fiber tow resin saturation are quantified. The motivation for understanding this flow behavior is to maximize the void velocity with respect to the resin, such that the voids can be successfully removed.

# NOTES

# VOLATILE-INDUCED VOIDS IN RTM PROCESSING FOR AEROSPACE: RESIN CHEMISTRY, VOID FORMATION AND FLOW

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Resin transfer molding has become a generally reliable and effective method for producing aerospace components with high microstructural quality. The elimination of porosity, the main manufacturing defect, has been addressed through several reduction strategies: intelligent resin infiltration configurations that ensure complete preform wet-out, vacuum application within the mold cavity and the removal of entrapped air, and resin formulations that limit volatile off-gassing during cure.

However, more recently, increased demand for composite use in challenging environmental conditions has led to the development of complex resin formulations, which provide improved part performance at the expense of significant volatile release during cure. The processing of such materials thus becomes considerably more challenging, and the relationships between resin chemistry, infiltration flow, volatile release and void formation must be re-evaluated.

The proposed paper describes a detailed study on volatile-induced void formation during the processing of a 177°C-cure heterocyclic modified phenolic-epoxy resin with potential for structural aerospace applications. First, the resin cure kinetics and volatile release are studied using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC) and a novel coupled dielectric cure monitoring (DCM)/Fourier transform infrared spectrometer (FTIR) set-up. Thus, the relationships between temperature, degree of cure, rate of cure, and volatile release rate are determined for a range of conditions. Then, the influence of process variables is studied using an instrumented lab-scale RTM mold which combines integrated heaters, pressure, temperature and dielectric monitoring sensors, and a clear mold wall allowing digital video capture. In the first instance, the mold is used to directly observe bubble nucleation and growth (or collapse) in neat resin at different time-temperature-hydrostatic pressure conditions. By these means, the relationship between resin state, process parameters and void size is clarified. Finally, the mold is used to manufacture carbon fiber/epoxy composite parts, and the influence of the injection conditions and resultant pressure gradients on void distribution and size is investigated.

Altogether, the study is expected to provide a comprehensive, fundamental understanding of the causal effects of resin volatile release and processing conditions on part quality. This understanding will in turn provide a basis for development of process maps that summarize the allowable parameter ranges for successful processing.

# NOTES

# COUPLING THE FORMATION, MOVEMENT, DISPERSION AND EFFECTS OF VOIDS IN RESIN INFUSION

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**Keywords**: capillary pressure, compressibility, coupled flow simulation

Much recent research has been devoted to the optimum flow velocity during resin infusion, at which a minimal amount of voids are created by mechanical entrapment at the flow front. Theoretical models and experimental methods have been developed in attempts to ascertain this optimal velocity. In parallel to this, other recent research has focused on the effects of voids on the mechanical properties of the resulting laminate. There still exists a large gap between the two research areas: the mobility and evolution of the formed voids, characterizing their final dispersion, and the resulting degree of detriment on the mechanical properties.

The mobility and evolution of voids requires characterization of various physical and chemical phenomena. Two strategies are suggested to assist in such modeling: experimentation at various flow rates and application of dispersion metrics to describe the void concentration. The former will be demonstrated by test infusions at the predicted optimum flow velocity for a particular fabric-fluid combination, as well as just below and above it. The latter will be demonstrated with void measurements of the ensuing infused panels.

An entire laminate is too often described with a constant homogeneous void content percentage, despite the fact that void concentrations are never spatially homogeneous after a resin infusion process. Previous work has developed various dispersion metrics for composites based on a machine learning based analysis. These metrics include nearest neighbor distance, free space length, size, 2-point correlation functions, and Minkowski Functions for "clumpiness." These metrics will be applied to describe the resulting voids in the infused test panels.

This work is meant as the initial stages to modeling the void mobility and evolution after formation at the flow front, and initial work towards correlating void size and distribution with the mechanical properties.

# NOTES

# MODELING HYSTERESIS IN LIQUID COMPOSITE MOLD FILLING PROCESSES WITH VOID FORMATION

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**Keywords**: LCM void, hysteresis

In order to analyze the formation of voids during the resin impregnation process, a one-dimensional solution based on two-phase flow through a porous medium, has been proposed by the authors in a previous work. This model leads to a coupled system of a nonlinear advection-diffusion equation for the saturation and an elliptic equation for pressure and velocity. The permeability is assumed to be a function of saturation, and then the continuity equation that governs the pressure distribution, includes a source term which depends on the saturation. The choice of relative permeability function can have a significant impact on predicted saturation. Furthermore, quality of numerical solution is affected by the numerical method to solve the saturation equation.

In order to test and evaluate the ability of the proposed model in LCM, results of numerical saturation were compared to experimental data obtained on a glass RTM mold under controlled manufacturing conditions. Saturation results for different experiments, injecting at constant flow rates, were compared with numerical simulation for the saturation. The validation of the mathematical model and the numerical technique for the saturation simulation was based on the experimental RTM filling with moderate constant resin injection rate of 0.1 ml/s. The authors found that numerical results obtained with a quadratic power law model for relative permeability using a flux limiter technique to simulate the saturation were in excellent agreement with the experimental solutions for this case, where capillary effects and air residual saturation were ignored. However, the model didn't reproduce the complete behaviour for lower and higher constant injection rate cases. Experimental results for the lower resin injection rate case showed the necessity to model for hysteresis relative permeabilities into the LCM processes with void formation.

Hysteresis behaviour of relative permeability and capillary pressure has long been recognized in other processes. It is well known that multiphase flow in porous media exhibits hysteresis. The relative permeabilities generally depend not only on the fluid saturations but also on the direction in which the saturations are changing. This is typically modeled by modifying the saturation dependence of the relative permeabilities. In this paper, a model for hysteresis in LCM processes is presented. This will require an hyperbolic system of conservation laws for the saturation equation with a history-dependent flux function. To validate the proposed model, numerical predictions for the saturation will be compared with experimental data.

# NOTES

# EFFICIENT METHOD TO CHARACTERIZE TEXTILE PERMEABILITY AS A FUNCTION OF FIBER VOLUME CONTENT WITH A SINGLE UD INJECTION EXPERIMENT

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**Keywords**: permeability, liquid composite molding (LCM), measurement methods, resin flow, resin transfer moulding (RTM), fabrics/textiles

Preform permeability is a key material property to predict the resin flow pattern in Liquid Composite Molding (LCM) technologies. It is a measure of the ability of a fibrous reinforcement to allow fluids to pass through it and depends on the preform characteristics, like fiber orientation and fiber volume content (FVC). In the past years, several methods and set-ups have been developed for permeability determination, but a standard procedure is still missing. Recent efforts by the scientific community have led to common guidelines for unidirectional (1D) flow experiments to measure in-plane permeability values. Nevertheless, to fully determine in-plane permeability, unidirectional tests in three directions are needed for each FVC, resulting in a material- and labor-intensive experimental characterization.

In this work, we investigate a new concept to perform 1D permeability tests. The aim is to reduce the experimental effort by characterizing permeability as a function of FVC in a single test. The testing method we present can be carried out in a set-up similar to the one proposed in the guidelines, with the simple addition of a single transducer, sensing the fluid pressure in the preform, and without the need of transparent molds. An algorithm is developed to determine the flow-front evolution and the preform permeability profile directly from the pressure signal. This method allows the characterization of permeability through zones with different FVC in the same experiment. Comparison of measured permeability values with data obtained by traditional tests shows consistency of the results.

# NOTES

# INFLUENCE OF PREFORMING TECHNOLOGY ON THE OUT-OF-PLANE IMPREGNATION BEHAVIOR OF TEXTILES

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**Keywords**: liquid composite moulding(LCM), compaction, permeability, hydrodynamic, impregnation

Some of the most common Liquid Composite Molding (LCM) processes, e.g. Advanced RTM, provide an out-of-plane impregnation of the fiber structure. Due to the emerging pressure distribution the fiber structure is hydrodynamically compacted during the out-of-plane impregnation. A prediction of the behavior of the fiber structure under these conditions is highly complex due to the strong interdepence between the pressure distribution, the compaction behavior, and the impregnation behavior. Therefore, the determination of process parameters such as the injection pressure or the tool closing velocity is nowadays often accomplished by time- and cost-intensive trial-and-error procedures. However, efficient manufacturing requires a methodical approach based on well-founded knowledge about the influence of material parameters, process parameters, and preforming technology on the hydrodynamic behavior.

In this study different possibilities to influence the hydrodynamic behavior of textiles by preforming technology are investigated. A novel measurement apparatus, capable of reproducing the conditions during out-of-plane impregnation, is applied for this purpose. It comprises sensor technology for out- of-plane permeability determination simultaneous to online compaction monitoring. Therefore, the interdependency during the impregnation process, which has a strong influence on the material behavior, can be taken into account. Samples of textiles treated with sewing and binder technology are compared to untreated reference samples. It was observed, that sewing increases the permeability of the textile. The increased permeability reduces the pressure within the cavity, which in turn reduces the occurring hydrodynamic compaction. Different sewing thread thicknesses allow a variation of the hydrodynamic behavior. The influence of thermoplastic binders is mainly caused by pore-space reduction, which decreases the permeability. Pre-treatments based on preliminary compaction cycles, which can be easily implemented in a preforming process, increase the reproducibility of the hydrodynamic behavior. The results contribute to a more systematic usage of LCM processes with out-of-plane impregnation since they lead to a deeper understanding of the impregnation phase and offer application-related solutions. Therefore, the results can be used to increase process efficiency and component quality.

# NOTES

# RIGID TOOLING FOR OPTICAL 3D WETTING PERMEABILITY MEASUREMENTS

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**Keywords**: permeability, optical, through-thickness

The through-thickness component of a reinforcement's permeability has become more popular recently, as processes like vacuum infusion (VI) and resin film infusion (RFI) become more common in industry. Through-thickness flow is the most time-consuming resin path in VI and RFI, so industry has demanded the data necessary to simulate such flow. Data for through-thickness permeability is scarcer than in-plane measurements, though, as through-thickness measurement methods are more difficult and relatively new.

A simple method for through-thickness permeability characterization is by point-infusion into the top of a stack of material. Nedanov and Advani first presented this method along with a solution for the flow geometry at the point the resin reaches the bottom of the mold in point-infusion. More recent work has simplified the solution for the three unknown fabric permeability components from such a test. Various complications exist with this method which reduce its accuracy (in reference to other measurement methods) such as the flow singularity of point-infusion, capillary pressure effects, and the compressibility under a vacuum bag.

This paper presents a new adaptation of the point-infusion method using rigid tooling comprising thick transparent acrylic sheets for both the top and bottom of the mold. Thus, a hybrid between standard 2D radial testing and 3D point infusion is employed. In this way, the difficulties of process modeling associated with the thickness gradients under a vacuum bag are eliminated for 3D point-infusion permeability testing. The other issues of flow singularity and capillary effects will be commented upon. The robustness of this test method will be evaluated by comparison with other permeability measurement methods.

# NOTES

# VACUUM ASSISTED PROCESS® – TECHNOLOGY FOR LARGE AEROSTRUCTURE COMPONENTS

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With the increase in use of composite materials on primary structures of commercial and military aircrafts, cost-efficiency has become an increasingly important factor when choosing the manufacturing process for a part.

The patented Vacuum Assisted Process® (VAP®) allows low production costs by the use of dry non crimp fabrics, an out of autoclave curing and a very reliable process. The use of high areal weight materials and the possibility to build integrated structures make the technology especially suited for the manufacturing of large aerostructure components.

This presentation gives an overview of the key characteristics of the technology and the archived developments that allowed the introduction of the technology into the production of class 1 aircraft parts like the B787 and the A350 Rear Pressure Bulkhead. Furthermore an outlook is given on required further developments of the technology, to play a significant role in future aircraft programs.

# NOTES

# A LUBRICATION APPROACH TO FRICTION IN FORMING PROCESSES WITH THERMOPLASTIC UD COMPOSITES

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A number of different deformation mechanisms can be identified in composite sheet forming [1]. A successful approach to analyse and predict the generation of wrinkles in doubly curved shapes is to reduce the set of laminate deformations to four essential deformation mechanisms, which are inter-ply and tool/ply slip, intra-ply shear and ply bending [2], and use these as basis for composites forming simulation. Therefore, we require the material's resistance against these deformation mechanisms, to be determined in separate characterization experiments.

In the context of composites forming, friction is known to be dependent on the sliding velocity, normal pressure, temperature and orientation of the fibers [3-7]. While an analytical model can adequately predict the friction of woven composites, as shown in [8], no equivalent model exists for UD composites. Researchers often assume the friction to be governed by hydrodynamic lubrication [1–5] with the existence of a resin interlayer, having a thickness of the order of the fiber diameter. So far, however, a mechanism that leads to the development of such a film has not been described yet, especially when the fiber direction is parallel with the sliding direction.

For this purpose an analytical model is introduced, that predicts the rheological behavior of the friction between the composite and the tooling surface, in which the fibers are oriented parallel to the sliding direction. This model is based on the filament distribution in the contact region, which is assumed to be constant in time. With this, the sheared resin interlayer and the dry friction between the fibers and the tooling surface can be analysed, possibly including wall-slip of the matrix material. A qualitative comparisons with experimentally obtained results of UD carbon PEEK and UD glass PPS is made, as well as a more in depth quantitative analysis with UD carbon PEEK. By adapting the model geometry on microscopic images of composite cross-sections, a qualitatively good agreement between experiment and model can be achieved.

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# NOTES

# PULTRUSION PROCESS FOR CONTINUOUS FIBER REINFORCED THERMOPLASTIC COMPOSITES

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**Keywords**: pultrusion, thermoplastic composite, braided fabrics, mechanical property

Recently, continuous fiber reinforcement thermoplastic composites (c-FRTP) have been attractive for the automotive and the aerospace field for the following reasons. Thermoplastic resin significantly reduces the molding time compared to the thermosetting resin. Moreover, thermoplastic resin has recycle ability and possibility of secondary processing because it becomes moldable above a specific temperature, and returns to a solid state upon cooling. Strength of the continuous fiber reinforced composites is higher than that of short fiber. However, the impregnation of thermoplastic resin into continuous fiber bundle is difficult because of the fiber assembly structure and high melt viscosity of the matrix. In order to solve this problem and to achieve high cycle molding, we have developed a new intermediate material in which reinforcing fibers and matrix resin fibers were commingled. Moreover, we have proposed one of the high-cycle molding for c-FRTP with fibrous intermediate material and pultrusion systems by using braiding technology. Braided fabrics and/or unidirectional fibers were pulled into the pultrusion die. The resin fibers of the intermediate materials were melted and impregnated into reinforcing fiber through the pultrusion process.

In this study, comingled fiber was used as intermediate material made from carbon fiber as reinforcing fiber and PA66 fiber as resin fiber. Two types of molded products were employed; one was the braided composite pipe and the other was the unidirectional rod covered by one layer of braided layer. The effects of filling ratio, pultrusion speed and die temperature on impregnation state and mechanical property were examined. Filling ratio was defined as the ratio of the cross-sectional area of commingled yarn (cross-sectional area of CF + cross-sectional area of PA fiber) to the cross-sectional area of the mold at exit side. From these results, the essential molding time was increased with decrease in pultrusion speed and increase in die temperature. In the case of the braided composite pipe, the increase in essential molding time resulted in the decrease in un-impregnation and void ratio and the strength was linearly increased with the decrease. On the other hand, in the case of the unidirectional rod covered by one layer of braided layer, there are many parameters which affected the void ratio such as change in braiding angle during pultrusion process, with or without middle-end-fiber, pultrusion speed. Improvement of impregnation states was effective to increase in mechanical properties of the moldings. In any case, effectiveness of braiding structure as reinforcements to impregnation was confirmed.

## NOTES

# MODELING OF UNSATURATED FLOW IN WOVEN FIBERS DURING DIRECT INJECTION-PULTRUSION PROCESS OF THERMOPLASTIC COMPOSITES

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**Keywords**: liquid composite molding, thermoplastic composites, pultrusion process, porous medium, permeability, dual-scale porosity, unsaturated flow, Darcy's law, finite element modeling

Injection-pultrusion is a manufacturing process in which reinforcing fibers impregnated with a liquid polymer are pulled through a die to form composites with a constant cross section. Whereas the impregnation step was not challenging with thermosets because of their low viscosity, it becomes a critical issue with thermoplastics due to their higher viscosity. Indeed the impregnation step has a strong impact on the quality of pultruded products, it can enhance the fiber wet-out and facilitate void suppression.

Thermoplastic pultrusion with prepreg products such as commingled yarns or powder-impregnated bundles have been already studied, however there are very few reported works on direct impregnation with injection within the die. In addition, the rare studies have not adequately addressed the issue of unsaturated flow in woven fibers.

During pultrusion process with direct injection of polymer within the die, the polymer movement can be modeled as a flow through dual scale porous media. The macro scale corresponds to the channels between the fiber bundles and the micro scale to the channels between the fibers themselves. Within the heated die, the fiber bundles can be considered completely surrounded by the liquid polymer but are unsaturated. Then as the fiber bundles pass the tapered die, cross-sectional area becomes smaller, the bundles begin to saturate and the excessive resin starts to flow backward.

This work applies to pultrusion process the model by Pillai and Advani (1998) who have modeled a polymer flow through a dual scale porous media. A sink term is added to the continuity equation, which represents the absorption rate of polymer by the bundles. Using the work of Gourichon et al. (2006), a new approach for the sink term in the mass balance is proposed. It takes into account the actual surface exchange between the two porous media and the potential exchanges between them. Darcy's law is applied to model the flow in the macropores and the porous fiber bundles are considered impermeable to provide accurate solutions. Then the sink effect is modeled through extra volumes attached to each node. This alternative approach makes easier the simulation with finite element method. Besides the polymer is modeled as Newtonian and pseudo-plastic fluid, the flow model is coupled to a heat transfer model and results are validated with data measured on a pultrusion line.

In conclusion, the main interest in the flow modeling of thermoplastic pultrusion process is not to determine the flow front location but the unsaturation rate evolution through the die. Such a result will help to better understand the process, to determine the key parameters: pulling speed, pressure within the die, permeability of the tapes, etc.

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# NOTES

# NUMERICAL PREDICTION OF IN-PLANE PERMEABILITY FOR WOVEN FABRIC WITH MANUFACTURE INDUCED DEFORMATION

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**Keywords**: CFD, meso-scale modeling, woven fabric, permeability

Previous studies have shown that the fabric permeability, which determines the impregnation with a liquid resin system, is highly sensitive to deformations of the fabric architecture. While a number of approaches are documented in the literature, in most cases based on macro-scale analysis and localised homogenisation of the fabric structure, reliable and accurate predictive quantification of the permeability tensor remains challenging, especially for woven fabric preforms under realistic manufacturing conditions.

In the manufacture of composite parts with double curvature employing liquid composite moulding processes, preforming introduces deformation of fibrous reinforcements. In the case of woven fabrics, reinforcements are subject to a combination of shear, compression and nesting.

Permeabilities of deformed fabrics can be predicted numerically at the meso- scale, based on modelling flow through a realistic geometrical model of the woven fabric and computation of the flow resistance. The geometrical description of fabric deformation can be obtained from a finite element solution of the material under load cases of shear and compression. However, this is not always viable since it is computationally very expensive.

Alternatively, fabric deformation can be modelled geometrically based on relative spatial constraints, self-imposed by the fabric architecture. The angle of yarn rotation, as well as changes in yarn cross-sectional area and shape are calculated as functions of shear angle and compaction level of the fabric. This geometrical method for assessment of fabric deformation is implemented in the TexGen modelling software. In addition, nesting between fabric layers can be approximated by a statistical sampling technique. This approach is supported by 3D image data of composites with woven reinforcement.

The latter approach is adopted in this study to generate detailed geometrical models of deformed unit cells. These are used as input for meso-scale flow simulations, the results of which allow the permeability of the deformed fabric to be predicted. The numerical prediction of permeability will be assessed and validated by experimental measurements on woven fabric specimens subjected to shear, compression and nesting.

# NOTES

# AN ADAPTIVE MONOLITHIC FINITE ELEMENT APPROACH FOR THE NUMERICAL SIMULATION OF COMPRESSION RESIN TRANSFER MOLDING PROCESSES

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**Keywords**: compression RTM, finite elements, level-set, anisotropic mesh adaptation

The production of lightweight composites for automotive use has been forecast to grow rapidly in the future, mostly driven by economical and regulatory constraints for lowering energy consumption of vehicles. To achieve the desired energy-efficiency goal, the reduction of weight is critical and car makers are replacing conventional metal based parts by carbon based parts which present better strength per mass ratio.

While the traditional, metal-based designs are by now a mature technology and industry, the main impediment to composite broad scale adoption has been price and production rate. Indeed while metal parts can be made in seconds, typical composite processes are measured in minutes or even tens of minutes.

The newest process variants of Resin Transfer Molding (RTM), such as in-gap injection and compression RTM hold much promise for reducing manufacturing costs. Unlike in the conventional RTM process, the resin flows over the fabric and not through the fabric; then the upper-part of the mold moves downward so that the resin impregnates the fabric. Therefore, the resin flow is not limited by its viscosity and large complex parts can be molded much faster than in conventional high pressure RTM. The success of these new processes requires multiple industrial optimizations that can be significantly reduced with the help of CAE modeling.

However there are challenges for modeling those processes. The simulation must handle two types of flow, a Darcy flow in the low permeability fabric, and a Stokes flow in the gap on one hand, and the compression phase of a rigid body that pushes the fluids through a porous and eventually deformable fabrics on the other hand.

In this work we propose a finite element approach to handle Stokes-Darcy flows, applied in industrial compression RTM processes.

For that, a monolithic approach has been implemented. A single mesh is generated that contains all the important phases, described by implicit level-set functions. From these, property distributions (like permeability or viscosity) within the mesh are obtained and used for computing the velocity and pressure. These are given from the resolution of conservation equations using a mixed stabilized finite element solver. Interfaces between the phases are advected with this velocity, by a modified convected level-set technique and accuracy is ensured by using an automatic anisotropic mesh adaptation technique. Finally, coupling of flow with thermokinetics is done by solving heat and reaction equations, also through a stabilized finite element solver and by incorporating in the whole scheme the appropriate evolution of the rheology.

Validation has been performed by comparing numerical results to the ones issuing from the literature and from molded experiments of long carbon fiber composite using a development epoxy product of Dow VORAFORCE™. VORAFORCE™ is a Trademark of The Dow Chemical Company.

# NOTES

# EULERIAN APPROACH FOR COMPUTATIONAL FLUID-SOLID MECHANICS WITH CAPILLARITY ISSUES FOR RESIN INFUSION BASED PROCESS

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**Keywords**: Darcy, stokes, composites, level set, capillary porosities

Manufacturing processes by resin infusion (LCM) are competitive routes to elaborate composite structures with organic matrix, especially for large pieces in aeronautics . These processes consist in infusing a liquid resin into a stacking of fibrous preforms under the action of a mechanical pressure field applied onto this stacking where a stiff-distribution medium is also placed to create a resin feeding. However, although these processes are efficient, they still remain hard to control. Indeed, the most critical properties of the final part (the final thickness and the fiber volume fraction) are hardly predictable.

One of the main problems arising in the process is the possible formation of porosities as a consequence of the bad impregnation of the resin. The macrocopic models used to simulate and then optimize the process does not predict conditions leading to the micro/macro void creation because they do not include the multiscale nature of the porous media. This porous media is made from several yarns (bunch of fiber at mesoscopic scale) that gather multiples fibers (microscopic scale).

In this work, a numerical approach based on an eulerian framework for a thermo-reactive fluid flowing into and out of the fibrous media is proposed. The objective is to operate a scale transition to extract the mesocopical responses, i.e. at the scale of a bunch of fibers, as functions of some mechanical process parameters such as pressure and velocity fields, in order to establish scenarios for porosity creation and growth. To achieve this purpose, a fluid- solid contact model will be settled to represent the local contact, both static and dynamic, between the fluid and impervious fibrous solids at the mesoscopic scale.

This work is based on existing fluid-solid strategies for transient flows in deformable media at macroscopic scale. At this scale, two different numerical strategies have been investigated for coupling flows in both purely fluid region, ruled by Stokes equations, and a porous region of low permeability (down to 10−15 m2 ) governed by Darcy's equations . Both a decoupled approach, as proposed by [1], and a monolithic approach, as proposed by [2] have demonstrated their ability to solve problems with complex geometry in 3D severe regimes cases. In the first case, P1+/P1 mixed finite element is used for both Stokes and Darcy (primal form) domains depicted by two matching meshes, while P1/P1 approximation is used in the second case with the dualform of the Stokes-Darcy coupled problem stabilized by a Variational Multi-Scale method defined on one single mesh. Both Stokes-Darcy interface and fluid front are represented individually thanks to "Level-Set" functions, and some specific coupling conditions are prescribed on the interface separating both fluid and porous media

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## NOTES

# DIRECT NUMERICAL COMPUTATION OF FIBER ORIENTATION IN A SHEAR FLOW FOR NON-NEWTONIAN FLUIDS

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**Keywords**: fiber suspension, rheology, viscoelastic fluid

In Newtonian fluid, the fiber orientation is perfectly described by Jeffery's equation. In this study, a numerical rheometer is used to study the evolution of a fiber in a simple shear field for shear-thinning (power law) or viscoelastic fluids (Oldroyd-B or FENE-P). For shear thinning fluid the period of rotation increases whereas the fiber follows the same orbit as in Newtonian case.

For viscoelastic fluids, the period of rotation increases with the relaxation time (Weissenberg number) while the fiber is oriented along the vorticity axis. Consequently for viscoelastic fluids Jeffery equation cannot be used to predict the orientation of a fiber. In addition, analysis of hydrodynamic forces can explain the different scenarios.

# NOTES

# PROCESSING AND CHARACTERIZATION OF MULTI-SCALE COMPOSITES MANUFACTURED BY OUT-OF-AUTCLAVE RESIN FILM INFUSION

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This study involved the processing and characterization of laminates containing 0.3 wt% multi- walled carbon nanotubes (MWNT). The objective was to investigate the effect of the stacking strategy on the processing conditions and part quality, as well as the carbon nantubes (CNTs) dispersion and influence on the interlaminar and electrical properties of the multi-scale composite. The laminates were manufactured using an out of- autoclave resin film infusion process (RFI). The parameters that were varied were the resin film stacking strategy: grouped, in which resin film and fabric was stacked separately, and intercalated stacking strategy where the resin films were stacked between each dry fibre preform plies.

In order to model the resin infusion processes, compaction and through-thickness permeability measurements of fibrous reinforcement were performed. An analytical model was used to determine resin pressure distribution, resin flow front position, fibre-volume-fraction distribution, and laminate thickness change during the resin infusion process. The model was validated by tracking the laminate thickness in-situ throughout the cure.

The laminate quality was determined by taking micrographs of sections and measuring fibre volume fraction, void content distribution and analyzing the dispersion of the CNTs inside the manufactured laminates. The interlaminar properties were measured with double cantilever beam (DCB) tests using ASTM standard methods. A multimeter was used to record specimen resistance in four-wire mode when three-point bending load was applied using an electromechanical testing system. Two resistance measurement methods, i.e. surface and oblique, were used.

The analytical model was adequate to illustrate the flow process, estimate the needed resin quantity and predict the final laminate thickness. It underestimated the impregnation time and did not consider the flow process into the micro pores. The observation of the cross-section of the composites showed that CNTs agglomerate around the edge of the tows, creating non- uniform CNT distribution inside the composite. The intercalated stacking strategy exhibited superior characteristics during processing, compared to the grouped stacking strategy. There was no evidence that the laminate quality was influenced by the selection of the stacking strategy, especially because of the very low void content. According to the results, CNT filling in the matrix has a beneficial effect on the interlaminar properties of the composite part: an increase of the fracture toughness values of more than 13% could be measured. The electrical responses of CF-CNT-epoxy to flexural load are different from that of CF-epoxy composites.

# NOTES

# PACKING AND PERMEABILITY PROPERTIES OF E-GLASS FIBRE REINFORCEMENTS FUNCTIONALISED WITH CAPSULES FOR SELF-HEALING APPLICATIONS

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**Keywords**: smart materials, fabrics/textiles, mechanical testing, resin flow

The in-situ repair of low-extent cracks, such as those developing through fatigue or barely visible impacts in fibre-reinforced polymers could be made possible by extrinsic self-healing. Capsule-based approaches consist in the embedment within the polymer matrix of micron-size capsules, which are constituted of a protective but brittle shell and a liquid core containing the trigger agent for the healing phenomenon. When a crack propagates through the matrix, some capsules break and thus release their healing core. So far, the main type of damage that these healing systems aim at repairing, for composites, is the inter-ply failure within the resin pockets. Introduction and survival of the healing system is a crucial issue for the manufacturing of such composites. As yet, several techniques have been proposed, consisting in dispersing the capsules within the matrix prior to hand layup, or dipping the fibre reinforcement in a strongly capsule-loaded fluid. An alternative procedure consists in the dispersion of capsules onto the fabric by sieving. In literature, such a technique can be found for the functionalization of preforms with binders or tackifiers and it lends itself to scale-up.

The aim of this work is to present a reliable solution for the functionalization of woven glass fabric with healing capsules and to investigate the effect of the presence of capsules on the packing and permeability properties. Both investigations are relevant to composite manufacturing techniques such as LCM where the fabric stack is under compaction pressure and infiltrated by a fluid resin. The ability for the capsule loaded reinforcement to compact through nesting phenomena and its permeability are mutually linked, and they influence the achievable thickness and fibre volume fraction of the part. Interestingly for further manufacturing of self-healing composites by vacuum-assisted resin transfer moulding, the presence of capsules is found to modify both the compression and permeability responses in a non-linear fashion.

# NOTES

# COMBINING PROCESS SIMULATION AND SENSING FOR OPTIMISED COMPOSITES MANUFACTURING

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**Keywords**: sensing, modelling, identification, control simulation

Liquid composite moulding of advanced composites is a closed manufacturing process which rarely allows the operator to know what is happening in the mould e.g. during filling until resin emerges from the outlet gates or not even this if the mould is in an oven. The introduction of non-intrusive or through-the-laminate sensors that would signal when resin arrives at a specific location or at an outlet gate would help considerably the operator at the production floor but also during development to identify and to check the repeatability of the process. Furthermore, the introduction of viscosity sensors that can monitor the evolution of resin's viscosity in the mould and can provide quantifiable information for the curing of the composite can lead to the complete monitoring of the liquid moulding process.

In this paper, a resin arrival input is combined with a flow simulation software through an identification algorithm in order to calculate automatically unknown or varying parameters of the simulation such as viscosity or permeability tensor deviations. In this way the 'matching' of the simulated flow patterns with the realistic ones can be done automatically and then the following process optimisation through simulations regarding e.g. gate positioning and/or control will be based on the validated parameters ensuring the validity of the process optimisation phase.

Applications of the system include process monitoring and real-time visualization, data acquisition e.g. permeability measurements not limited by artificial constraints resulting from limited availability of analytical solutions and automated process control.

# NOTES

# COUPLING BETWEEN HEAT TRANSFER AND SATURATION: EXPERIMENTAL INVESTIGATION

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Liquid Composite Molding (LCM) and especially Resin Transfer Molding (RTM) are among the most commonly used fabrication processes for producing high quality and complex composite structural parts. The quality of LCM products strongly depends on the impregnation of the fiber preform during the mold-filling stage. During this step, the flow in the dual-scale porous media induces the creation of a partially-saturated zone, and consequently of voids, which drastically affect mechanical performances.

This study presents an original approach in which heat transfers are used to quantify the saturation profile of a composite during the impregnation. Even if several authors have contributed to a better understanding and modeling of the mechanisms of formation and transport of voids during injection, very few experimental approaches allowed a direct measurement of the saturation curve. We may mention in particular Nordlund *et al.* [1] and Ruiz [2] , who used optical measurements, or Labat [3] and Guéroult [4], who employ either conductivity or dielectric sensors.

An experimental bench that allows the injection of a model fluid into a unidirectional glass fiber cloth has been used. The model fluid has been chosen so that its properties are close to those of a resin. This device allows an accurate control of the fiber volume fraction, and of the fluid flow rate. Electrical heaters are placed on top of the preform and dissipate a uniform heat flux in the porous media. The thermal response of the material is measured by several thermocouples and wall heat flux sensors at different positions.

In a first step, a homogenization methodology based on asymptotic expansion has been performed at dual-scale in order to predict the thermal properties of the composite as a function of saturation. Additional experimental results allowed the determination of the thermal conductivity tensor of completely dry or fully-saturated samples. A simplified modelling of the filling front has been realized with FEM using Comsol Multiphysics. The saturation curve is modeled using several geometric parameters, which are subsequently identified by comparison of the experimental and numerical transverse heat fluxes. The saturation curve obtained through thermal analysis is finally compared with the one measured by a conductometric sensor, which was also used in the bench. A very satisfactory agreement is found between these two methods. Moreover, the results show that the saturation curves, and therefore the residual void content are strongly impacted by the value of the capillary number.

Finally, an alternative numerical approach is proposed, proving the feasibility of identifying the relative permabilities of each phase through thermal analysis.

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# NOTES

# LIQUID COMPOSITE MOULDING FLOW FRONT CHARACTERISATION BY MICRO-CT

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**Keywords**: LCM, VARI, resin flow front, micro-CT

Liquid composite moulding (LCM) is an increasingly common technique used to manufacture large scale composite structures in multiple transport industries. Vacuum assisted resin infusion (VARI) is a popular form of LCM due to the reduced tooling costs. However increased variability of VARI over other LCM processes can result in reduced part quality, with an increased probability of voids within the laminate. The production and manipulation of voids are known to be the result of a number of parameter, such as dual scale permeability of the glass fibres. Resin flow into dry fibres during LCM of large structures is highly non-uniform due to the anisotropic nature of composite materials strongly influencing final part quality. A number of point and distributed monitoring techniques exist to identify and record the resin flow front, however a review of the literature indicates that fully three dimensional techniques, which may provide a full characterisation of the advancing flow front to aid infusion strategies and to validate the increasing number of computational flow models, has not been extensively researched. This paper aims to fill this gap by investigating impregnation flow for the VARI process using X-ray microtomography (μ-CT) to provide a three dimensional characterisation of the advancing flow front, void production/distribution and progression.

Multi axial glass fibres and polyester resin used in the marine industry were investigated through partial processing of the VARI process to different stages. Firstly a 6cm diameter Perspex's mould was used to recreate a 15cm wide flat plate infusion, whilst achieving the desired aspect ratio for optimized μ-CT scanning. The infusion length was set to 45cm and a monolithic lay-up used to investigate a rectilinear flow front. Secondly comparable features to an industrial infusion were used on a larger 150cm long infusion to cause all of the expected flow anomalies that would not occur on a small lab scale flow experiment. Multiple ply drops, transitions regions from monolithic to sandwich structure, core grooves, and joints were all used to assess the effects of converging flow fronts, race tracking and mechanical entrapment. Samples from each laminate were scanned using μ-CT to obtain 3D micro structural data of the advancing flow front and associated voids. This data was used to investigate the initial microstructure of the fibres and measure impregnation at each processing stage as well as the evolution of macro voids within the laminate. The results accurately illustrate the dual scale fingering effects of the advancing flow front at non-optimal modified capillary numbers as well as the effects of converging flow fronts on fibre impregnation.

# NOTES

# MONITORING NON-ISOTHERMAL POLYMERIZATION AND CRYSTALLIZATION OF CYCLIC BUTYLENE TEREPHTHALATE COMPOSITES MANUFACTURED BY RTM

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**Keywords**: thermoplastic RTM, pCBT, FOS, OBR, electric sensorization, distributed sensing

Cyclic butylene terephthalate (pCBT) composites obtained by isothermal polymerization have shown to be brittle and to require long cycle times. Non- isothermal routes, instead, allow tougher thermoplastic matrix. However, the main drawbacks of a non-isothermal curing route have been its low energy-efficiency, short processing windows and long cycle times related to the high thermal inertia of the moulds. New advantages in mould design, as the heating of the mould surface by electromagnetic induction or fast cooling down water cooling systems can overcome these problems, increasing the interest in the non-isothermal polymerization.

Monitoring mould filling, polymerization and crystallization processes of such a complex system -reactive thermoplastic composites- is essential in order to optimise the RTM process, since extrapolation of materials characterization results (DSC, SEC…) to real non-isothermal process is not trivial. Several monitoring methods have been proved to be useful to study the polymerization and crystallization of pCBT, but only a few –Fiber Optic Sensors (FOS), dielectric and electric sensors– can be integrated in a RTM process. Additionally, mould filling can be also monitored by different techniques, but only some of them are suitable for high temperature processes (FOS, pressure transducers, dielectric and electric sensors).

The evolution of traditional punctual FOS is the distributed sensing. Instead of limit the sensing area to the sensor length, as FBG, distributed sensing allows to measure along the full length of the fiber. Fiber Optic Distributed Sensors based on Raighleight scattering allows a temperature and strain measure every 2mm all along 2 km fiber using an OBR (Optical Backscatter Reflectometer).

In the present research work, the temperature of multiple zones (melting device, injection machine, runner system and mould) can be controlled, allowing complex thermal recipes that can optimise both, microstructure and cycle times. The scope is to analyse the sensitivity of two monitoring systems, electric sensor and Fiber Optic Distributed sensor, to the physical and chemical variations of the matrix in each step of the non-isothermal process. Sensor network embedded will be additionally used to monitor the resin flow and to measure dry areas after the injection.

The combination of distributed optical sensing and electric sensors is suitable, since FOS is useful for monitoring mould filling and shrinkage , and electrical resistance of the resin can be used to monitor the conversion degree. Based on the monitoring results, cycle time has been considerably reduced (30%).

# NOTES

# INCREASING THE ROBUSTNESS AND RELIABILITY OF CFRP PRODUCTION PROCESSES THROUGH SYSTEMATIC ANALYSIS AND PROCESS MONITORING

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**Keyword**: process robustness, vacuum infusion, process monitoring, TDR, flow front, state of cure

Within the aerospace industry, one reason for the high cost of composite parts is the limited understanding of the manufacturing processes compared to established manufacturing processes for metal parts. This lack of knowledge leads to uncertainty regarding the impact of process deviations and to high costs for quality assurance and rework. In order to improve the understanding of the manufacturing processes and as a result to increase their robustness it is necessary to apply a methodical approach. One possible approach comprises of a modeling step during which the manufacturing process is structured and displayed graphically. The created model can then serve as a basis for a process analysis during which important process parameters are collected and their effect on the process output is characterized.

By applying the above mentioned method, key parameters for infusion processes can be identified. These include the temperature within the preform, the applied vacuum and pressure, the flow front of the resin and the state of cure. Especially during the introductory phase of composite manufacturing processes, a precise monitoring of these parameters can help identify the right settings of the manufacturing equipment much faster than by only inspecting the finished parts. Process monitoring can thus provide great benefits to save time and resources. To monitor the above mentioned parameters, different types of sensors can be applied. These range from simple thermocouples to measure the temperature to point pressure sensors, which allow detecting the hydrodynamic pressure within the preform. To monitor the flow front different approaches such as optical fiber sensors and areal sensor arrays can be used. The changing dielectric properties of the thermoset resins during cure allow a prediction of the state of cure. An interesting method to monitor the infusion and the curing of the part is the time domain reflectometry (TDR). This method has already been validated for glass fiber preforms and room temperature curing resin systems, with good results regarding flow front detection and state of cure measurement. The method is particularly interesting as it requires only a transmission line as a sensor, keeping the effect on the laminate to a minimum. For high performance aeronautic parts, this provides a great advantage to other more bulky sensor concepts. In the presented research, the applicability of the sensor concept for the boundary conditions of aeronautic applications such as carbon fibers and metal toolings is investigated using a commercially available low cost TDR reflectometer.

# NOTES

# DEVELOPMENT OF AN INNOVATIVE PREFORMING PROCESS FOR THE HIGH-VOLUME AUTOMOTIVE SECTOR

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**Keywords**: preforms, filling, permeability, flow-visualization, macro-permeability, micro-permeability

As the first step to mass production of CFRP components in the automotive sector has been made with the BMW i3, a set of innovative and efficient production processes for CFRP-parts have been developed within the BMW Group during the decade. With these processes BMW has proved that structural CFRP-parts can be produced in short cycle times, at low costs, in an industrial setting.

Within the scope of this project the focus lies on the preforming process, which delivers semi-finished three-dimensional textile structures for a subsequent injection process. The main target of the project is a strong reduction of material waste, leading to high savings in the variable costs.

To reach this target a new technology is proposed using direct robotic placement of dry rovings without any intermediate textile products, in a near-net-shape position relative to the final part. Thus not only material waste but also material cost is addressed, by avoiding production costs for textiles.

Focus of this presentation is the investigation of the filling behavior of these new perform-structures. For these investigations several experimental facilities have been used, including; permeability and compressibility characterization, a two- dimensional HP-RTM tool and a flow-visualization rig. Efforts concerning process integration and adaption to high-volume production rates are still in ongoing development.

# NOTES

# TOOL VIBRATIONS FOR THE ADVANCEMENT OF THE VACUUM INFUSION PROCESS

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**Keywords**: vacuum infusion, vibrations, cfrp, aerospace

In order to advance the performance of conventional Vacuum Infusion for out-of- autoclave aerospace applications several techniques have been proposed.

However few ideas have been proposed using dynamic means during the process such as the audio frequency vibrations applied to the injection pressure and the mechanical vibrations to the mould. In the latter case, a RTM mould is vibrated during and/ or after the filling process by applying external mechanical vibrations to the mould in order to eliminate dry spots and improve quality (1,2). With respect to vacuum infusion, research has been contacted towards improving the fibre compaction by external means such as a (pulsed) press (3) but besides the difficulty of reproducing this technique in real scale, the permeability of the preform is decreased leading to higher injection times. On the other side, some results have shown that the application of vibrations during the curing of prepregs with Quickstep may improve part quality (4,5).

In the present work, vibrations are introduced in the vacuum infusion of advanced cfrp parts with the aim to reduce void content and improve preform compaction. A vibration mechanism was developed that can shake a small flat tool at various frequencies and magnitudes. Instead of applying the vibrations before or during the filling, the vibrations are applied after the end of the filling phase. In this way, vibrations can enhance the escape of entrapped voids as well as to improve fibre compaction. The latter can be achieved in conjunction with the vacuum pressure enhanced by the existence of resin which serves as a lubricant for the fibre redistribution.

First trials showed an increase in fibre volume content from 53% in the conventional VI to 57-59% in the vibration case whereas the void content increased from 0.57% to 0.83% -1.2% depending on the vibration frequency and magnitude. Based on these preliminary results, an upscale system is under construction for the manufacturing of a 1m by1.5 m cfrp skin and results on its performance will be presented at the conference.

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# NOTES

# IN-MOULD GEL-COATING WITH A SEPARATOR LAYER

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Many composite applications require a gel coated surface for cosmetic or durability reasons. The most common method of preparation is to paint or spray the mould tool, allow the coating to gel before laminating onto the tacky surface. During gelation, a proportion of the styrene (which is a major component of the unsaturated polyester resin system) is lost from the open mould tool as vapour into the workshop/environment. The Styrene Producers Association has recently recommended implementing a 20ppm limit that ensures employee safety. A new "ultra-low styrene content spray gelcoat" is reported to have achieved an average styrene concentration of 22.3 ppm relative to 54.3 ppm for a "standard gelcoat" [1].

In-mould gel-coating with a separator layer [2] involves placing the reinforcement material and a spacer medium into the mould before introducing a resin that permeates the reinforcement material on one side of the separator and/or introducing a gel coating material on the opposite side of the spacer medium. Laminate resin injection may precede or follow gel coat injection. Simultaneous injection of both resin systems would require more complex flow control.

The paper will report experiments to develop this in-mould gel-coating process for resin transfer moulding using a double glass plate mould. Data on workplace styrene levels (average styrene concentration 0.24 ppm), surface quality measurements by DOI Wavescan and pull-off adhesion strengths will be presented.

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# NOTES

# EFFECT OF SURFACE TREATMENT FOR CONTINUOUS FIBERS ON IMPREGNATION AND MECHANICAL PROPERTIES OF THERMOPLASTIC COMPOSITES

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**Keywords**: surface treatment, thermoplastic, mechanical property, continuous fiber

Continuous fiber reinforced thermoplastic composites have been attractive material system due to the recycle ability and secondary processing in recent years. The fabrication of continuous fiber reinforced thermoplastic composite involves two problems. The first one is that thermoplastics as matrices generally have high melt viscosity so that it is difficult to impregnate resin into reinforcing fiber bundle. To overcome this problem, several kinds of intermediate materials to shorten impregnation time have been developed. Since thermoplastic resin is located close to reinforcement fiber bundle in the intermediate materials, impregnation performance of thermoplastics is excellent. The other one is low interfacial properties between the fiber and matrix. It is considered that interfacial properties in continuous fiber reinforced thermoplastic composites can be characterized by the wetting ability and chemical interaction between fiber and matrix. Wetting ability would affect resin impregnation state during molding, while chemical reaction affects composite strength. Therefore, interface design of CFRTP is very important to obtain composite materials with improved processability and mechanical performance.

The objective of this research is to improve the both impregnation state and interfacial properties by using surface treatment on carbon fiber. To achieve this objective, surface treatment with low molecular weight polycarbonate (PC) were used for CF/PC composite. In order to investigate the effect of low molecular weight PC on interfacial properties and impregnation state by changing sizing content, interfacial shear strength was examined by micro-droplet test and unimpregnation ratio were examined by optical microscopy. As a result, interfacial shear strength was increased and unimprengation ratio decreased with an increase in sizing content. Consequently bending strength of UD composite was increased with an increase in sizing content. From these results, both impregnation state and interfacial properties of CFRTP were confirmed to be improved by using low molecular weight PC on carbon fiber.

# NOTES

# FLOW ANALYSIS SOFTWARE FOR RTM: DESIGN AND APPLICATIONS

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**Keywords**: flow simulation, flow modelling, optimization, resin transfer moulding, resin infusion.

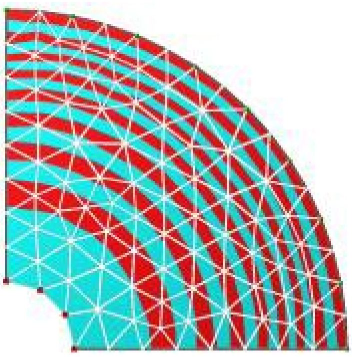
## Introduction

The main goal of the development and implementation of flow analysis software is to create a tool for part designers and manufacturers, to design of a robust production method for high quality composite parts that meet structural, visual, and most important, economical requirements. In the particular case of an injection moulding process, this translates into designing an injection strategy and – if applicable – choosing flow aids, that results in a process which guarantees low void content (no dry spots) and has low sensitivity for variations in preforming and process parameters. To meet our user's goals, we implemented software that is extremely fast, very accurate and highly robust.

## Modelling the RTM process and implementation in software

At the core of our model for Liquid Injection Moulding of composites is Darcy's Law, extended to three dimensions. Solving this equation is not particularly difficult, and our implementation uses a combined Finite Element/Control Volume Method. As was shown in [1] for 1D linear line elements and 2D linear triangular shell elements, both FEM and CVM formulations are equivalent for the discretisation of the pressure and velocity fields. This result extends to 3D for the linear tetrahedral element. For the progression of the flow front, the VOF method is used, which allows for a very efficient and accurate implementation.

**Table 1:** *Simulation of injection of a quarter disk (worst case for accuracy). The model (with 167) elements is shown at the left, the table lists the resulting injection times, error compared to the analytical solution (1411 s) and the calculation time on a laptop with Windows 7 64-bit, Intel i7-2640M CPU at 2.8 GHz and 8GB RAM. Model parameters: inner radius 200 mm, outer radius 1000 mm, thickness 1 mm, fibre/volume fraction 50% and permeability 1e-9 m² (isotropic) [3].*



| *Elements* | *Result* | *Rel. Error* | *Calc. time* |
|---|---|---|---|
| 57 | 1381 s | 2.1% | << 1 s |
| 167 | 1410 s | 0.07% | << 1 s |
| 696 | 1409 s | 0.14% | < 1 s |
| 1008 | 1411 s | - | 1 s |
| 3868 | 1411 s | - | 1 s |

For the calculation of temperature and curing history [2], we use a streamline upwind method for the convection terms. The solver, which exploits the structure of the stiffness matrix, is very fast: non-isothermal calculations with curing typically take only twice as much calculation time as an isothermal run.

## Designing injection strategies that work, adding SALT

Any injection strategy consists of one or more of the following types: point injection, edge injection or peripheral injection. Comparing those three basic types [4] leads to the unavoidable conclusion that peripheral injection is preferred because it results in the shortest injection time and the smallest variation in flow front progression speed. In practice however, mould construction limits the possibilities and the designer should be able to compare different strategies in short time to arrive at the best trade-off between complexity, robustness and cost of the manufacturing process. Part of this design process can be automated (sensitivity analysis, location of ports), and we implemented a scripting language to support optimization, called 'SALT', which has multiprocessing as a core capability.

Optimization complements exploration of the possibilities. Injection strategies should not result in dry spots and the major cause (apart from choosing a wrong strategy) is race tracking. Next major cause for voids is stagnation of flow and the opposite is true: ensuring that the resin flows everywhere will minimize void content.

### Selecting consumables: flow media and membranes

For the infusion of larger parts like wind turbine blades, boat hulls and bridges, one-sided moulds with a flexible bag are used because a double sided stiff mould becomes impractical. The consequence is that the only way to create a pressure difference is to draw a vacuum which limits the pressure gradient available to drive the resin flow. In addition, if there is a considerable height difference, part of the vacuum is also required to lift the resin. Flow media, like meshes and grooved cores, can assist to speed up the resin flow but practical experience learns that the ratio of the permeability of the reinforcement and flow medium is limited, otherwise there is a high risk for voids and (local) air traps. The other limit is the height of parts which can be infused in a single shot. In theory, vacuum is able to lift a resin column of almost 10 meters, but in practice this limit is about 6 meters because a pressure gradient is required to make the resin flow to the highest point. We eliminated this barrier by designing a 2-step process, which consists of two separate shots under a single bag in continuous reinforcement, and creation of a 'perfect' weld line using VAP membrane and an arrangement of vacuum and feeding lines.

### Conclusion and future work

An extension to full 3D, tetrahedral elements that can be freely combined with the shell and line elements, is about to be released. In combination with the very fast RTM-Worx solver and a completely new 3D mesh generator that can generate very coarse meshes, the software will allow fast design of injection strategies. Under the control of SALT, the speed and accuracy is a first requirement to make optimization feasible: one of the target applications is real-time process monitoring, adjusting the model on-the-fly for permeability variations.

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## NOTES

# EXPERIMENTAL ANALYSIS OF FLOW BEHAVIOR IN THE FLAX FIBER REINFORCEMENT WITH DOUBLE SCALE POROSITY

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**Keywords**: natural fiber, liquid composite molding, permeability, wettability, fiber swell, liquid sorption

Recently, natural fibers attract great interest from automotive industry by virtue of their environmental friendliness as well as high specific stiffness. Liquid composite molding (LCM) processes have a high potential for the fabrication of natural fiber reinforced composite structures by dint of high fiber volume fraction to enhance mechanical performances and low processing temperature to minimize fiber degradation. The resin impregnation process into natural fabrics involves complex phenomena and difficult to optimize, however, because the hydrophilic nature of vegetable fibers leads to a poor wettability with thermoset resin and the fiber swell due to liquid sorption into fibers alters the microstructure of fiber reinforcement during the mold filling process. Moreover, all these phenomena are strongly coupled and take place in different scales i.e. from the macro scale in the large sized preform level to the micro scale at the single fiber filament level. Therefore, it is required to establish a process model considering all these coupled phenomena as well as to characterize the material properties such as fiber swell, liquid sorption, resin wettability and preform permeability.

We used flax woven mat as a preform for the resin transfer molding (RTM) process. The saturated and unsaturated permeability were measured using two different liquids: a liquid with good wettability and low viscosity (e.g. water) and a liquid with poor wettability and high viscosity (e.g. synthetic oil). For the liquid with good wettability and low viscosity, there was no difference between the saturated permeability and unsaturated permeability. On the contrary, the unsaturated permeability values were lower than the saturated permeability values when the liquid with poor wettability and high viscosity was used. This difference is assumed to come from the delayed tow saturation behind the macroscopic flow front due to the low viscosity and poor capillary wicking into the fiber tow in the case of unsaturated flow. On the other hand, we observed a significant difference for the saturated permeability values for the two different liquids. It is supposed that the fiber swell due to the liquid sorption into the fiber filaments change the actual fiber volume fraction and fiber diameter during the mold filling process.

We performed an experimental measurement of liquid sorption and corresponding change of fiber diameter. Liquid quantity absorbed into fiber filament was measured with time by a centrifuge and a microbalance. The corresponding change of fiber diameter was measured by a microscopic image observation. Based on the experimental results, the sorption kinetics was modeled by Fickian diffusion law and Fick's diffusivities were identified for the two liquids. Through a capillary rise experiment, capillary wicking inside the fiber tow was modeled considering the gravity effect.

Finally, we propose a process model for the resin flow into the natural fiber reinforcement with double scale porosity considering the fiber swell due to the liquid sorption into the fiber filament and the delayed tow saturation in terms of resin wettability and tow microstructure. We provide a comparison between the model prediction and the experimental measurement for the transient flow front progress.

# NOTES

# CAPILLARY EFFECTS ON FLAX FIBRES REINFORCEMENTS; COMPARISON OF CHEMICAL AND MORPHOLOGICAL EFFECTS ON THE LOCAL WETTING DYNAMICS

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**Keywords**: capillary motion, sustainable composites, surface energy

The push for more sustainable materials, either biodegradable or fully recyclable has motivated the composite industry to look increasingly at bio-based reinforcements and resins. Caring about the sustainability of both the reinforcements and the resin implies to avoid some mechanical treatments that could generate unhealthy products or wastes. The chemical surface state of the sustainable reinforcements is thus hard to control, but of first importance.

Indeed, the increased use of Liquid Composite Moulding (LCM) for composite manufacturing in the transportation industry, the complexities of the parts and quality requirements have increased tremendously. Those effective and low cost processes are thus an interesting way to manufacture bio-based composites. Observations of a large amount of voids in bio-based composite calls for an improved understanding of the local phenomena involving voids creation and evolution. In order to control the void predictions in composite parts, models have to be developed for fibrous preforms filling and defects location prediction.

For a better understanding of the local phenomenon leading to void formation at different flow rates, it is first required to analyse which effect is dominant at the local scale during impregnation of the bio-based reinforcements. Two main un-controlled factors can be the source of the void formation at the local fibre-resin interface: the fibre surface chemistry and the fibre surface morphology.

The purpose of this work is to study the influence of flax fibre surface chemistry on the local wetting dynamics. Morphological aspects at the reinforcement scale are also investigated. Flax reinforcements have been submitted to a thermal treatment in order to degrade the hemicelluloses that are responsible for the hydrophilic behaviour of the flax fibres. Then chemical dosage of the hemicelluloses ratio in the reinforcement will be given. Measurements of the surface energy of both treated and genuine flax fibres will be presented. Void content and mechanical properties of composites reinforced by both reinforcements will also be discussed as basis for understanding which effect is predominant.

# NOTES

# SHEAR VISCOSITY DATA OF NATURAL FIBRE COMPOUNDS FOR THE MODELING OF POLYMER PROCESSES THROUGH REVERSE ENGINEERING

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**Keywords**: injection molding, flax fibre compound, shear viscosity data, reverse engineering

This work describes a reverse engineering tool that has been developed to characterise the rheological shear behaviour of natural fibre filled thermoplastic compounds. In this investigation, a compound with 20% of flax fibers with a length of 2mm is considered within a polypropylene matrix material. To perform numerical simulations for the different steps of the injection moulding process, the rheological data is governing the flow inside the mold influencing the fiber orientation and length. Standard rheological measurements on a dual bore capillary rheometer with die diameters equal to 1mm are not possible due to the presence of larger particles in the compounds disturbing the polymer flow field. Experiments were performed on a standard hydraulic injection moulding machine equipped with a mould to produce tensile bar specimen according to ISO 527. In this mould, a pressure sensor and different temperature sensors are mounted linked to a data acquisition system able to track data at a frequency of 1kHz. Different injection flow rates are used in combination with different cooling water temperatures. With the natural fibre filled material, it is not possible to change the temperature of the melt significantly due to the thermal sensitivity of the natural fibres. The temperature of the melt is kept constant at 190°C. Based on the different experiments, the shear viscosity data has been fitted as function of shear rate and temperature. To fit this rheological behaviour, a matlab script has been developed. In this script, a power law description for the viscosity as function of shear rate and temperature has been used. The possible presence of slip phenomena along the mould wall was also investigated. To describe the slip phenomena, an exponential function have been used to link the slip velocity to the occurring shear stress.

The characterized shear viscosity data has been used for an industrial part to illustrate the appropriateness of the developed measuring strategy and modelling work.

# NOTES

# MOLD FILLING SIMULATION IN RTM PROCESSING OF NATURAL FIBER COMPOSITE MATERIALS

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In order to manufacture high quality green composite parts, advanced processing techniques should be used. Liquid composite molding (LCM) techniques like resin transfer molding (RTM) or vacuum infusion (VI) have proven to be suitable for processing natural fiber/thermoset resin composites. Numerical modeling of the mold filling stage optimizes the process and reduces the production costs, since most of the trial and error involved in mold design (inlet and vents location) can be done rapidly in a computer program. Darcy's law is widely used to model the fluid flow through a porous medium, and it is also extensively used in modeling flow processes in composite materials manufacturing. This law allows predicting the flow front position inside the mold cavity during the filling stage. Fluid viscosity and reinforcement permeability are the main properties involved in Darcy's law. In contrast to synthetic fibers, the permeability of natural fiber reinforcements does not necessarily remain constant along the wetted region of the fabrics throughout the infiltration process, because the porosity can change as the fibers absorb fluid and swell. In this work, two models were proposed to simulate the flow front movement during the one dimensional RTM processing of composite materials reinforced with natural fibers. These models consider the effect of fluid absorption and fiber swelling on the porosity and permeability of the preform. The homogeneously variable permeability model, that was the first approach to model the process, considers that the permeability of the preform decreases with time due to fiber swelling, but the change in permeability is uniform throughout the entire wetted perform and is only a function of the injection time. On the other hand, the permeability field model, considers the fact that different regions of the wetted perform experience higher or lower fiber swelling depending on the amount of time that they have been immersed in the fluid. This leads to a field of permeability along the wetted fiber bed. The results showed that all models that take into account the swelling of the fibers predict a much slower flow front movement that the model that assumes that permeability is constant over time. The experimental data was much better fitted by the permeability field model than by the constant permeability model when a swelling fluid was used in the permeability test.

# NOTES

# DESIGN OF A QUASI-UNIDIRECTIONAL FABRIC FOR RTM PROCESS WITH HIGH FLUIDITY THERMOPLASTIC: LONGITUDINAL PERMEABILITY AND MICROSTRUCTURE

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**Keywords**: quasi-unidirectional fabrics, thermoplastic composites, glass fibres, microstructure, permeability models

The project ThermoplAstic Process for Automotive Structure (TAPAS) was kicked in 2012, gathering several French industrial and academic partners. The mean idea of the project is the use of a high fluidity polyamide suitable for Resin Transfer Molding (RTM) process. The different polyamides under development in TAPAS should have viscosity values between 1 and 20 Pa.s. That is two orders of magnitude less than usual thermoplastics. However, these viscosity values remain higher than the ones for epoxy or polyesters used in "classical" RTM. According to Darcy's law, the other key parameters are the applied pressure and the permeability. Capillary pressure might also ease the filling of the mold by increasing the volume-averaged velocity of the resin.

The present work focuses on the permeability role in the TP-RTM process. It has been decided to work on unidirectional preforms made of glass fibres. The idea to increase longitudinal permeability of fabrics has been previously undertaken in the 1990's with the Injectex flow-enhancing fabrics [1,2]. Two variants of a quasi-unidirectional fabric have been designed and elaborated for TAPAS with the same goal but using different concept than the Injectex. These two woven fabrics are constructed with a calibrated "spacer" yarn between two warp yarns in order to improve the hydraulic efficiency (ratio between the hydraulic conductivity of channels over their cross-sectional area) of volumes between the yarns, i.e. the macropores.

The two quasi-unidirectional fabrics are compared with different Injectex fabrics and other existing UD fabrics such as a stitched one previously studied [3]. The comparison is based on the experimental measurements of permeability values, in satured and unsatured (flow front monitoring) conditions, at different fiber volume fractions, with silicon oil. Permeability is mainly measured along the warp direction of UD stacks. Intrinsic permeability (Darcy's permeability) values, along the three directions of the space, for the two variants of UD can also be predicted with a numerical method developed in [4] and based on a mean-field homogenization approach. It relies on the quantitative geometrical description of the macropores and supposes the existence of definite macropores bounded by yarns. When this latter assumption is not valid, higher order geometrical descriptors can be used instead [5]. An analytical approach for saturated permeability along the direction of fibres developed in [3] is also applied over the different UD tested.

The two lasts methods for determination of permeability are based on microstructure parameters either fibres and yarns characteristics or structure of macropores and micropores. For this reason, all UD fabrics have been assembled in preforms and impregnated by vacuum infusion with a polyester resin. This manufacturing process was chosen because of its similarity with the TP-RTM. Samples are cut out and imaged with optical and scanning electron microscopes.

Finally, a discussion is proposed on prediction of injection times for high fluidity polyamides through the proposed quasi-unidirectional fabrics. First results about RTM composite parts with polyamide and glass UD preforms are also presented.

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# NOTES

# A MICROMECHANICAL MODEL TO SIMULATE CAPILLARY FLOWS IN DUAL SCALE POROUS MEDIA

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**Keywords**: Darcy's law, dual scale flow, capillarity, saturation

Liquid Composite Molding (LCM) is increasingly used to fabricate composite parts by resin injection through fibrous reinforcements in various areas such as the aerospace, automotive or marine industries. In this family of composite manufacturing processes, the resin flow in the mold cavity is usually modeled by a macroscopic model based on Darcy's law. The simulation of LCM processes is based on this approach, which successfully predicts the evolution of the average velocity of the flow front and the pressure field in the mold. However, most engineering textiles are porous media of two scale porosity, inside which a dual scale flow occurs during mold filling. The macroscopic pores between the fiber tows are filled first when the velocity of the flow front is high such as in rigid mold injections, for example in Resin Transfer Molding (RTM). On the contrary, when the velocity is low such as in resin infusion for example in Vacuum Assisted Resin Infusion (VARI), the microscopic pores inside the fiber tows, which are between one and two orders of magnitude smaller, begin to be filled first by capillarity. These phenomena are important because they govern the distribution of voids in composite parts made by resin injection and hence play a key role on the quality of high performance composites. One way to characterize these phenomena consists of conducting capillary rise experiments in fibrous reinforcements.

The present paper reports on a novel way to model dual scale flows through porous media based on a detailed description of its "directional fiber volume content". This new notion together with capillarity plays a key role on the way resin flows in engineering textiles. A dual scale flow can be modeled in the unit cell of an engineering fabric by a simple micro-mechanical approach combining capillary effects with permeability. A new numerical algorithm was devised to predict the dual scale flow through unidirectional fibrous reinforcements without taking into account the progressive saturation of fiber tows. The comparison with capillary rise experiments clearly demonstrated the key role played by saturation. By incorporating saturation in a refined version of the algorithm, it was possible to reproduce capillary rise experiments on the computer. In addition to providing a novel way of modeling dual scale flows, this first result opens up a new possibility, namely to predict the optimal flow velocity in LCM by numerical simulation instead of using complex experimental setups or carrying out lengthy experiments.

# NOTES

# HIGH TEMPERATURE VARTM USING LARC-PETI-9 POLYIMIDE RESIN

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The use of composites materials as primary structures for aerospace applications has increased dramatically over the past decade. To ensure successful application of temperature resistant composite structures for high speed aerospace vehicles, it is necessary to develop material systems that meet specific properties and process requirements. NASA LaRC has recently developed a series of new phenylethynyl terminated imide (PETI) resin systems to meet the processing requirements associated with high temperature vacuum assisted resin transfer molding (HT-VARTM) of aerospace components. In the current study, the cure reaction kinetics and viscosity of the LaRC-PETI-9 resin system has been investigated using differential scanning calorimetry (DSC) and parallel plate rheometry. The measured cure rate versus degree of cure data and viscosity versus degree of cure data were fit to mathematical models using a nonlinear regression analysis program. The results indicated that the LARC-PETI-9 resin curing reactions are complicated, and a two-part kinetics model was required to adequately describe the curing progress. The data obtained during the initial part of the reaction were fit to an autocatalytic cure kinetics model. The data acquired during intermediate and final stages of the reaction were fit to an nth order rate equation. The degree of cure separating the two kinetics models and the kinetic parameters of each model were functions of reaction temperature. Results of the kinetics analysis indicate the curing reaction mechanics below 340°C is different than the mechanism above that temperature. Overall, the kinetics model calculated results agreed well with the measured values. Isothermal rheological measurements of LARC-PETI-9 resin were performed to measure the viscosity as a function of time during cure. The viscosity data were obtained at temperatures ranging from 290 °C to 320 °C. At each measurement temperature, the viscosity versus time data was converted to viscosity as a function of degree of cure using the cure kinetics model. The viscosity versus degree of cure data sets were used to develop the viscosity model for the LaRC-PETI-9 resin. The viscosity model is a simple mathematical expression and considers the effects of both temperature and cure on viscosity. Comparisons between the calculated and measured viscosities show that the developed viscosity model accurately predicts the evolution of LaRC-PETI-9 resin viscosity with temperature and degree of cure over wide range of temperatures, and will be useful in defining and optimizing the HT-VARTM processing parameters of LaRC-PETI-9 resin. The cure kinetics and viscosity models were incorporated into a HT-VARTM process simulation model. The results of the simulation model for an aerospace structural component will be presented and discussed.

# NOTES

# MODELING AND VALIDATION OF THROUGH THICKNESS FLOWS IN FULLY WETTED TEXTILES DURING CONSOLIDATION

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**Keywords**: through-thickness flow, modeling, resin bleeding, consolidation

Consolidation of fully wetted textiles occurs in different processes in composite manufacturing. Examples are the bleeding phase in prepreg processing or prepreg press processes. When the consolidation induces a flow in compaction direction, a time dependent distribution of fiber volume fraction in through thickness direction is present. In order to reach a high degree of homogeneity in the final composite part, the evolution of the distribution has to be quantified.

In this paper, a 1D-simulation model is presented, which describes the through thickness flow of resin and the textile deformation as a consequence of laminate consolidation in a fully saturated condition. The input data for the model have been determined experimentally and consist of compaction curves of wet fiber preforms, as well as the saturated permeability as a function of fiber volume content. For the validation of the model, bleeding experiments with 1D-through thickness flow were performed, where the fluid pressure at the bottom of the laminate is measured. The comparison of the experimental data with simulation curves shows a good agreement. For slow compaction processes, where viscoelastic effects during textile compaction can be neglected, non-dimensional analysis was performed, which allows the identification of the impact of process parameters on the bleeding time.

# NOTES

# ANALYSIS OF MULTI-SCALE EFFECTS ON THE PERMEABILITY OF FABRICS FOR LIQUID COMPOSITE MOLDING

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**Keywords**: liquid moulding processes, process modelling and simulation, multiscale numerical simulation

Accurate permeability prediction of fibrous textiles for liquid composite molding (LCM) is a cumbersome task, due to the hierarchical structure of the preforms and thus to the multi-scale nature of the problem. The uncertainty primarily lies in the modification of the structure of the textile during the processing, which is due to the compression in the mold and to the subsequent injection of the resin. In this contribution we analyze these two stages separately for an 8H Satin Weave textile. Firstly we show that by means of simple numerical models, the experimental data on permeability cannot be recovered over the whole range of porosities. Therefore we investigate the causes of this discrepancy. The effect of the textile compression is analyzed by an analogy between the yarn and a viscoplastic-like material. The compression curve is fitted with experimental data and the simulations yield the resulting intra-yarn porosity distribution. Subsequently, the effect of deformation due to resin flow is addressed. The fluid-structure interaction at the fiber scale is analyzed by means of a statistical model, which yields the local change in porosity through topological invariants. It is found that microscopic effects (e.g. fiber clustering) non-negligibly affects the overall permeability, which suggests that a better insight on the microscopic physics may be useful for understanding the uncertainty between experimental data and numerical simulations for real fabrics.

# NOTES

# AIR EVACUATION IN CONSOLIDATION MODELING OF OUT OF AUTOCLAVE PREPREGS

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**Keywords**: multi-physics simulation, out-of-autoclave, porosity, consolidation, impregnation, air evacuation, heat transfer, OoA

Composite parts are traditionally cured in an Autoclave with the application of external pressure. To circumvent draw backs of autoclave manufacturing, such as high capital investment and part size constraints, in the early 90's Out-of- Autoclave curing (OoA) was introduced as an alternative.OOA curing is typically taking place in an oven, complemented by a single sided mold, closed under vacuum with a flexible membrane.

Since OoA prepregs often contain a significant amount of air as received from manufacturer, the air flow and evacuation of the part becomes a parameter that can strongly influence the progression of the resin-fiber wetting process and subsequently porosity formation by air entrapment.The air evacuation through the composite part can be influenced by the initial resin deposition pattern on the prepreg, the length of the part or its distance from the vacuum source, the quality of vacuum during processing as well as potentially inhomogeneous resin cure. Non homogeneous heat and pressure distribution encountered primarily in thick parts, in combination with low pressure available can lead to finished parts with high porosity content and porosity zoning.

This work presents an approach for coupling air and resin flow in one dimension, including heat transfer and the influence of temperature to the permeability, viscosity and compaction state of OoA prepregs. Numerical approaches have been developed to correlate gas pressure boundary conditions to ply filling time, assuming resin flow within the material is Darcian. These models have been integrated to a commercial software package in order to model the evolution of impregnation and the consolidation process Out of Autoclave for a monolithic composite part. The material description is done in a macroscopic level, nevertheless incorporating material behavior information derived by actual prepreg characterization.

# NOTES

# PROCESS MODELING OF COMPOSITE MATERIALS – A HOLISTIC AND GENERIC SIMULATION TOOL USING POROMECHANICS

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**Keywords**: process modeling, a holistic approach, poromechanics, FE modelling

The industrial interest in processing science for composites material has increased dramatically during the last few years. A more scientifically approach is required to substitute the tradition of trial and error in manufacturing of composites since the empirically based manufacturing strategies are economically not competitive. A typical manufacturing chain consists of reinforcement performing, forming, mould filling, consolidation and curing. Also the shape distortion due to consideration of the residual stress state is considered as a manufacturing and assembly effect. All the above mentioned sub-processes are well understood in isolation, and both the scientific and industrial communities are able to analyse them separate from each other. Today's trend in composites manufacturing is however to cut down the number of operations required to produce a component. Therefore, all of the above steps may be combined into a single processing operation that leads to increasingly complex process in which many sub-processes occur simultaneously on different spatial and temporal scales.

In this context we are developing a generic and unified poromechanical finite element framework, which can cover modelling of all different range of manufacturing processes from infusion like processes via prepregs to forming and press-forming using a single element formulation. In the present contribution a continuum finite element framework is being used to model flows at two different scales, as well as the filling phase (flow front) of a deformable preform where compressibility of each phase is being considered. In particular, the moving flow front is modelled using a discontinuous inner boundary developed as intrinsic feature of our continuum framework without any use of other pre-developed methods; such as level-set. In consequence, both pre- (gas flow) and post-filing phases can be easily modelled by just changing boundary conditions.

The idea is also to show the versatility of the present continuum framework in various aspects of the composites processes. In view of this we will develop the dual-scale coupled displacement-pressure, non-linear finite element routine. The approach is then applied to a representative numerical example displaying different aspects of composites manufacturing consisting of gas and liquid flow, micro-infiltration, fibre plies and fibre network deformation; all modelled using same single and generic finite element formulation.

# NOTES

# AN EFFICIENT SCHEME TO MODEL RESIN FLOW IN A DEFORMABLE POROUS MEDIA USING RTM INFUSION SIMULATION

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**Keywords**: liquid composite molding, process modeling, compaction

In Liquid Composite Molding (LCM) process, complete saturation of reinforcement with resin during the injection step is crucial for successful part manufacturing. To assist with this task, flow simulation software has been successfully developed and tested to help with flow predictions during Resin Transfer Molding (RTM) process. Since then, this software has also been utilized for other resin infusion processes. The main difference between RTM and most other LCM infusion processes is that in RTM, the mold is rigid and thus cavity and reinforcement experience no deformation during infusion. For other infusion methods the mold is compliant and preform dimensions (thickness) change during the flow.

To capture this physics, two approaches have been followed. First approach was to neglect the deformation and assume that it is small and will not influence the dynamics of flow. The second approach was to develop specialized code for coupled deformation and pressure field. This approach tends to be computationally inefficient and so far only partially successful. The third possible approach would be to use the RTM solver with additional correctional steps to address the physics encountered due to the use of compliant molds. This approach has been previously attempted but is computationally expensive which precludes from use of flow simulations for optimization and control when molding complex geometries. Our paper will introduce a new methodology to address the physics and maintain computational efficiency. The constitutive material behavior will also be analyzed to provide viable model representation. Finally, the error introduced due to our simplification is compared with the previous two approaches.

# NOTES

# IMPREGNATION OF COMPOSITES AT THE UNIT CELL LEVEL

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**Keywords**: composites modelling, impregnation, weaves, FPM, FE

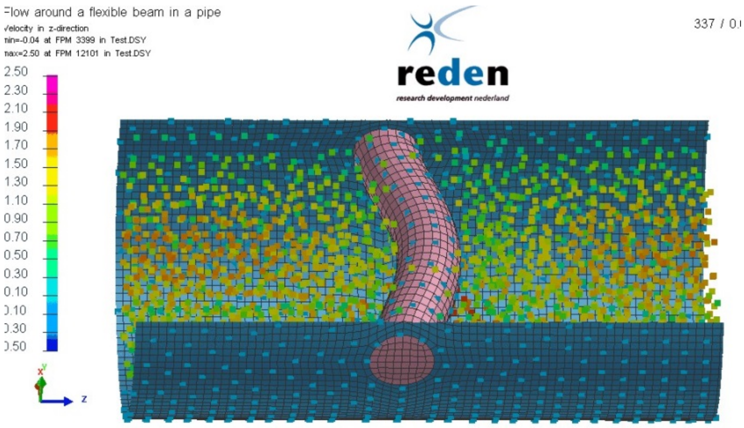
Thermoplastic composites have a good potential to improve the cost-effectiveness of polymer composites. The impregnation process of standard thermoplastic materials is however not straightforward (or impossible) due to their high viscosities. The newest types of thermoplastics have however much lower viscosities, increasing their potential for the impregnation process.

The prediction of the impregnation process is however not straightforward. The effective permeability of the fabric is highly affected by the fibre distribution. Furthermore, the fabric will deform during impregnation. Processing the fabric is recognised to have a major effect on the resulting properties. The impregnation process of the fabrics should be void free in order to reach optimal properties.

Prediction of the impregnation process is generally done with continuum models. These models often use permeability measurement as input. With the measured (anisotropic) permeabilty a flow simulation is done and the evolving flow front during impregnation can be predicted.

Here, the prediction of the permeability is addressed with a new modelling technique developed by ESI software. The Finite Pointset Method (FPM) is a meshless modelling technique which can incorporate the Fluid Structure Interaction (FSI) between the thermoplastic material and the still dry preform.

The prediction of the model will be validated with a simple case; the deformation of a rubber rod in a pipe due to polymer flow. The flow rates in the experimental set-up remain low, limiting the Reynolds numbers, and preventing flow instabilities. The measured deformation of the rubber rod in the flow is used for validation. Below, a picture shows the deformation of a rubber rod in the flow, the coloured dots in the picture represent the points in the Finite Pointset Method.




The applicability of the FPM modelling technique to the impregnation of composites is shown by impregnating of a plain weave unit cell with a thermoplastic material. A unit cell of a plain weave at the unit cell level (inter yarn) is used in the exercise. As a first assumption no impregnation at the intra yarn level is assumed, allowing a surface based approach for the interface of the yarns.

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# NOTES

# Abstracts of Posters

# SIMULATION OF THE COMPRESSION RESIN TRANFER MOULDING PROCESS FOR FAST CURING RESINS

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A substantial reduction of impregnation flow length is the most particular advantage of the compression resin transfer moulding process, making it an ideal candidate for high volume manufacturing. Processing limits could be identified by representing the interaction of viscous forces, fabric compaction and permeability over time.

Lightweight structures are of particular benefit for CO2 reduction in various fields of transportation. However, carbon fibre reinforced polymers have not yet achieved a broader success due to slow manufacturing processes, making them inadequate for high volume production. The compression resin transfer moulding (CRTM) process is characterized by having a very short impregnation flow in out-of-plane direction compared to the resin transfer moulding (RTM) process, where flow is mainly in-plane. Furthermore improved interfacial properties have been reported for the CRTM process, indicating a synergistic effect between short cycle time and part performance [1].

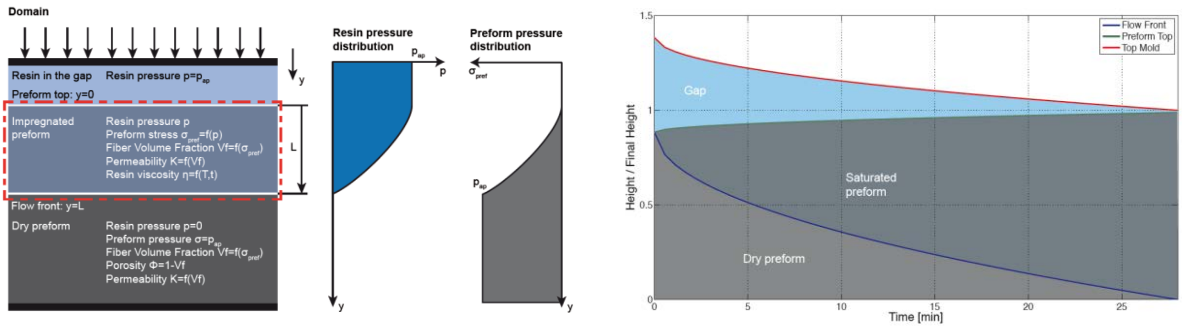


**Figure 1.** *Left - description of the simulation domain; centre - evolution of resin pressure and preform pressure in the domain; right - evolution of the impregnated domain over time at constant pressure.*

One specific attribute of this process is related to the viscous forces of the flow permeating in the preform influencing the fibre compaction and hence the out-of-plane permeability of the unsaturated preform [2, 3]. The flow process was modelled by establishing the corresponding constitutive laws for a one-dimensional domain as shown in Figure 1, taking into account the respective physical interactions and solved in an explicit time integration scheme. The model showed agreement with experiments using high viscosity liquids at different constant pressures. The results on fast curing resins revealed processing limits for highly compactable preforms, such as non-crimp fabrics or unidirectional braiding, which are prone to reduced permeability and hence bad impregnation.

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# NOTES

# REINFORCEMENT OF PARTIALLY CURED AEROSPACE STRUCTURES WITH B-STAGED PATCHES

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**Keywords**: B stage cure, bearing reinforcement, kinetic modelling of epoxy resins, RTM6

This work contributes to the EU FP7 Cost effective reinforcement of fastener areas in composites (CERFAC) programme. This method is being developed for the reinforcement of fastener areas for the connection of the floor beam to the fuselage. The area of the rivet will be reinforced by a load introducing patch while the rest of the part will have a nominal thickness. The part and the patch are produced separately and the cure is interrupted at an intermediate B-stage. Later the patch will be co-cured on the part to achieve a full cure in both components, i.e. uniform glass transition temperature, $T_g$, and elastic modulus in the matrix.

This approach results in stress reduction around the hole, simpler geometries of the single parts and high flexibility of reinforcement in the patch. The reinforcement can be adapted to the individual load case by the choice of the reinforcement material, layup and resin system. The co-curing stage of the cure eliminates a bonding step and results in the ideal case of a monolithic part.

In this work, the approach of co-curing is applicable for hole reinforcements for connections loaded in bearing. To achieve this, a detailed analysis of the curing reaction is required. It is necessary to predict the degree of cure, $\alpha$, and $T_g$ evolution for any time/temperature profile so that the cure cycles of the part and the patch may be optimized. The influence of the interrupted curing cycle on the mechanical and thermal properties is investigated. The influence of the interface treatment is also discussed.

# NOTES

# SIMULATION OF MULTILAYER PREFORM IMPREGNATION DURING VARTM PROCESS

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Use of fiber reinforced polymer composites has increased significantly in automotive and aerospace industries during the recent years.

For composite manufacturing, VARTM (Vacuum Assisted Resin Transfer Molding) is a very promising solution for the industry. It is cheaper than RTM (Resin Transfer Molding), especially for the manufacturing of large and complex geometry parts. However, this process needs to be more understood to be widespread as it should be. In this process, the part thickness varies due to the hydro-mechanical coupling that exists between the reinforcement compaction and the resin pressure. Moreover, the resin flow occurs in the planar and through the thickness direction because of the use of distribution medium.

Many researchers have modeled the filling of the mold by VARTM. To describe the resin infiltration, some of them have used 2D simplified model without modeling through the thickness flow. Other researchers have developed 3D models that are more precise but require considerable amount of computation time.

In this paper, a new approach for simulation of VARTM mold filing is presented. This method provides high precision results with low computational work. It results from the combination of two models:

- Infusion in a single layer preform model: it take into account the hydro-mechanical coupling without considering the through the thickness flow. This model uses CVFEM (Control Volume Finite Element Method) in 2D½ (2D elements with a degree of freedom on the thickness). It is validated analytically and experimentally.
- Injection in the multilayer preform: this method allows to add the flow between 2D layers in the through the thickness direction. However, it does not consider the hydro-mechanical coupling. This model uses CVFEM with 2D elements for planar flow and 1D elements for through the thickness flow. It is validated as well by using numerical and experimental results.

The resulting VARTM model is validated experimentally. It allows the manufacturing simulation of complex multilayer shape parts. The model takes into account the use of different materials and the variation of layer orientation.

# NOTES

# INFLUENCE OF CHEMICAL-STITCHING BINDER TECHNOLOGY ON PREFORM PERMEABILITY

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For the mass production of complex high performance composites the Resin Transfer Molding (RTM) process is a very promising approach [1, 2]. Within the appropriate process chain the manufacturing of three dimensional textile preforms plays a key role in terms of reaching short process cycle times. Based on textile, semi-finished products like woven and non-crimped fabrics are draped in shape. The automated fixation of these preforms is actually performed by the use of adhesive binders, to achieve process stability. These binders are applied between the layers of the textile semi-finished products. The used binder materials, as well as the application method, have an influence on the infiltration process of the matrix material into the fiber textiles [3]. In this study a very new preform fixation technology called "chemical-stitching" [4] is investigated and evaluated against the state of the art technologies using binder powder or thermoplastic binder fleece. To characterize the infiltration behavior of the different binder technologies, permeability measurements are done for each system. The reference material is a unidirectional-glass fiber woven fabric (type: 92146; Company: PD Interglas GmbH). Furthermore the study evaluates the influence of the binder amount to the permeability. Therefore three different amounts of binders are examined in this study. For the permeability measurements a 1-D test setup is used, which is mainly geared to unidirectional fiber textiles. To do the measurements under suitable conditions, specialized sensors are used to detect the flow front and the pressure history in the cavity of a 200mm thick steel construction.

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# NOTES

# EFFICIENT TEXTILE CHARACTERISATION: INDUSTRY-FOCUSSED PERMEABILITY AND COMPACTION EVALUATION

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**Keywords**: Permeability, Compaction, Liquid Composite Moulding, Resin Transfer Moulding, RTM, Compression RTM, VARTM, Flow simulation, Characterisation, Textile

Liquid Composite Moulding (LCM) processes are popular manufacturing methods used to produce composite components. A wide range of LCM processes exist such as RTM, Compression RTM, VARTM etc providing production volumes from low to very high and with low to high set up costs. The common ground between these processes is the infusion of resin through a dry fibrous reinforcement in a closed mould. As a result, the key parameters of the material that influence the filling of the fibre preforms are the permeability and compaction response. Permeability governs the flow of resin through the dry reinforcement. The compaction response of a reinforcement is a measure of the resistance the material offers to being deformed through the thickness. These parameters are very important when considering process simulation, quality control checks and material development, however current methods to characterise textiles are time and material intensive. As a result, this limits the use of such procedures in industry. A Marie-Curie Actions project is currently underway to investigate and develop prototype methods for the efficient characterisation of textiles used in LCM processes; specifically characterisation of the permeability and compaction response. This paper presents the results of the first stage of the project; working towards efficient characterisation methods. A wide range of experiments have been conducted to identify the principal material parameters affecting the permeability and compaction response. Studies on factors such as the number of layers of textile per preform, in-plane shear, nesting and comparisons between in-plane testing methods (rectilinear and radial) have been completed on two carbon-fibre textiles. These results will be combined with results from the literature to identify the parameters which are of prime importance to material characterisation; thus allowing the primary focus of characterisation tools to be established. A survey of industrial users of LCM processes will be undertaken to determine the requirements of large, medium and small businesses across a range of industries: automotive, aerospace, wind energy, sports equipment manufacturers, textile manufacturers, etc. This will allow the desired outcomes

of characterisation techniques to be identified – balancing required accuracy against cost and time. A prototype efficient characterisation method for the permeability and compaction response of fibrous textiles will be presented. This will combine the results of the physical testing, literature studies and industrial surveys. It is envisaged that this methodology will combine experimental and simulation approaches to account for a range of process conditions in an efficient manner.

# NOTES

# A STUDY ON THE FILTRATION OF NANO AND MICRO PARTICLES IN LIQUID COMPOSITE MOLDING PROCESSES

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Industrial processing of thermosetting fiber reinforced composite materials usually involves an impregnation stage where the resin is injected into a mold that contains the dry fibrous preform. Once the reinforcement is saturated and the mold filling is completed, resin is left to cure and the part can be removed from the mold. Nano or micro particles are sometimes added to the resin, in order to improve specific properties of the material or decrease costs and resin shrinkage during curing. When liquid composite molding (LCM) techniques are employed using a filled resin, particles are transported by the resin and can be captured by the fibrous bed, which acts as a filter. The trapped particles can decrease preform porosity and therefore its permeability, increasing the resistance to flow. The high suspension viscosity and the decrease in preform permeability caused by filtrated particles might be responsible for dry spots, poor saturation of the fiber tows or longer production cycle time. Moreover, as the filtration takes place, a gradient in the suspension concentration can be developed along the flow path. This inhomogeneous particle distribution remains in the material microstructure after the resin cures, leading to uneven properties of the finished part. Understanding filtration phenomena during LCM processing of composite materials using particle filled resins and their effects on composite final microstructure, performance, and processing conditions is crucial to successfully manufacture defect free composite parts. In this work, composites were obtained by resin transfer molding using two types of fillers: glass micro spheres and nano clays. The filtration of the particles and its effect on processing conditions and composite final microstructure was studied. The effect of the processing variables, such as injection pressure, suspension concentration, reinforcement architecture, fiber volume fraction and resin viscosity, on the filtration phenomenon was analyzed.

# NOTES

# ADVANCED COMPUTATIONAL STRATEGIES FOR FAST AND RELIABLE GATE ARRANGEMENT PRE-DESIGN OF RESIN INFUSION PROCESSES

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**Keywords**: Simulation, Liquid Composite Molding, Model Order Reduction

Simulation of flows involved in composites manufacturing processes remains nowadays a recurrent challenge due to different and frequent numerical issues: (i) the first concerns the usual double scale encountered in the reinforcement preform; (ii) the second is due to the degenerated geometries usually encountered (e.g. plates, shells, extruded profiles or the combination of all them), all of them requiring extremely fine meshes when using standard discretization techniques; (iii) the necessity of solving many direct problems when optimizing the process conditions (inlet or vents optimal location, optimal mould temperature and/or flow rate in particular in the case of reactive processes), among many others. In this work we are revisiting the use of model reduction strategies for performing efficient simulations, process optimization and simulation based control. The use of appropriate in-plane-out-of-plane separated representations allows also addressing efficiently models defined in degenerated domains and exhibiting rich behaviors throughout the thickness coordinate. On the other hand, the consideration of processing variables, as for example material permeabilities, injection pressure, flow rate, mould temperature, etc. as extra-coordinates within a PGD based model order reduction allows one to define appropriate efficient optimization and control of processes. Finally, we will address complementary computational tools based on considering a purely geometrical approach, as the one based on the level-sets, for locating optimally inlets and vents in infusion processes at the pre-design stage.

# NOTES

# INVESTIGATION OF SKIN-CORE ADHESION IN RESIN INFUSED SANDWICH PANELS

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**Keywords**: Resin Infusion, Sandwich Panels, Fracture

Liquid Composite Molding (LCM) encapsulates manufacturing processes such as Resin Transfer Molding (RTM), Vacuum Assisted Resin Infusion (VARI), etc. where a liquid resin is injected into the reinforcing material (preform) which is placed in a mold. The goal is to have the reinforcing material fully saturated by liquid matrix and be free of voids. For the case of VARI, the pressure in the mold cavity containing the preform is kept lower than atmospheric pressure. Composites such as sandwich structures where a thick low density core is placed between two composite face sheets are finding increased utilization in the aerospace where light weight and high stiffness are of primary concern. However, cellular core structures such as the foam core panels are vulnerable to impact loads which may lead to delamination and consequently significantly reduce its load bearing capabilities. One method to circumvent this is to increase the fracture toughness or the face-to-core bonding.

Currently, commercially available foam cores with circular perforations through its thickness are used for the purpose of enhancing flow through top to bottom face sheets. In this work, VARI has been used to manufacture several PET foam core based sandwich panels with glass fiber face sheets. Specifically, five types of sandwich panels were manufactured which include plain foam core, square pattern grid perforated foam cores with and without fiber strands being introduced through them. The conventional foam core sandwich panel was set as a baseline for comparison of fracture toughness against sandwich panels with perforated cores having fiber strands introduced through the holes. In addition, through-thickness compression was done for all core types. Preliminary tests have indicated that perforated foam cores with the highest perforation density and fiber volume fraction demonstrate the highest fracture toughness. They not only assist in mold filling but also resist the progression of the crack growth. This was followed by cores with fewer perforations having lower fiber volume fractions in the holes and cores with fiber free perforations when comparing the fracture toughness and the ability to arrest crack progression compared to conventional plain foam core panels.

Finally, the transverse compression tests revealed that the peak stresses prior to foam failure increase substantially for foam cores with perforations and the peak stresses increase as the perforation density increases. The introduction of fiber strands in the holes appears to have a mixed effect. While the average peak stress for the lower density perforated cores with fibers in the perforations is lower than its counterpart (same perforation density but without fibers), the contrary appears to be the case for the cores with higher density perforations.

# NOTES

# PROCESSING AND MECHANICAL CHARACTERIZATION OF GLASS FIBER REINFORCEMENTS USING GO NANO PARTICLES

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**Keywords**: Graphene Oxide, Nanocomposites, Resin Infusion

Recent advancements in nano reinforced materials have allowed enhancement and tailoring of mechanical properties of resulting composites. The addition of nano particles to the polymer matrix has been shown to produce nanocomposites with enhanced mechanical and multifunctional properties [1]. The processing characteristics of epoxy resin mixed with Graphene Oxide (GO) were investigated in this study. Firstly, GO was synthesized from graphite powder with modified Hummer's method [2]. GO was fully dispersed in ethanol solution and was mixed in epoxy resin under magnetic stirring. The mixture was then stirred further and heated to remove the solvent.

Four layers of biaxial glass fabric were cut and sealed under a vacuum bag. The glass/epoxy laminates were prepared by the vacuum assisted resin transfer molding (VARTM). The flow characteristics of the reinforcement (permeability) and the resin viscosity are highly dependent on nano particles concentration in the resin system. Three different concentrations of GO (0.05%, 0.1% and 0.2%) were mixed in the epoxy resin. The viscosity of the resin was measured using a Rheomoter, the flow front progression of the resin in the glass reinforcement was also monitored at several time steps. Different injection schemes were also trialed for better dispersion and reduced filtration of nanoparticles in the laminate.

Preliminary results indicate that the addition of GO nanoparticles leads to increase in resin viscosity and decrease in gel times with increasing GO concentration. Significant non homogenous dispersion of nanoparticles in the final composite was also observed. The nanoparticle distribution is directly related to the injection scheme, particles size, laminate length and thickness. The distribution of nanoparticles within the laminate was studied using a UV vis spectrophotometer, also the laminate cross sections at different flow lengths were analyzed using scanning electron microscopy (SEM).

Mechanical test results reveal that the addition of nanoparticles may enhance energy absorption and reduce through-thickness damage of resulting structures under impact loading. Further impact and flexural testing will be carried out on the manufactured samples.

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# NOTES

# A MULTIFUNCTIONAL PVT DEVICE FOR THE CHARACTERIZATION OF THERMOPHYSICAL PROPERTIES OF THERMOPLASTICS IN EXTREME THERMAL CONDITIONS.

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The control and optimization of heat transfers during the forming of thermoplastic parts is of primary importance since they directly impact the quality of final parts. The modelling of these transfers requires an accurate knowledge of the thermo-physical properties of the matrix, but also of the parameters describing the crystallization kinetics. The experimental determination of these parameters induces the use of many instruments, which is time consuming. To address this issue, a home-built PvT instrumented mould, dedicated to thermoplastics (including high-performance ones), has been designed to measure and/or identify several properties from a single experiment and in thermal conditions close the process ones.

This device allows the moulding of cylindrical samples of 8mm diameter and 16mm thick while controlling the applied pressure (up to 200 MPa) on the sample and the temperature cycle on its surfaces (the cooling rate can reach more than 100K/min between 300°C and 120°C). This mould is designed such as heat transfer is 1D within the radius of the sample. Variation of volume as well as heat transfers between the sample and the mould are recorded using LVDT and heat flux sensors, respectively. To cool the sample with a high rate, we use the thermal inertia of the mould combined to an initial induction heating. A 1D conduction model with a moving boundary coupled to phase change kinetics is used to describe the behaviour of the sample. Specific volumes as well as transverse thermal conductivity in melted and solid states can be estimated as function of temperature. Parameters of crystallization kinetic model are also identified. Our methodology is illustrated with results obtained on PEEK matrix.

# NOTES

# CHARACTERIZATION OF CAPILLARY PRESSURE EFFECTS IN LIQUID COMPOSITE MOLDING

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**Keywords**: Capillary pressure, Compressibility, Coupled flow simulation

In flow simulation of LCM processes, the flow velocity by Darcy's law is related to the permeability and porosity of the reinforcement material, the applied pressure gradient, and the fluid's viscosity. At typical industrial flow-rates, the pressure gradient during LCM is reduced by a capillary pressure that acts upon the resin to draw it into the tightly packed fibers. At low fiber contents or high pressures, this effect is insignificant. But modern high fiber contents and the slow through-thickness direction flow in vacuum infusion (VI) and resin film infusion (RFI) have rendered the capillary pressure a significant determinant of the pressure gradient. So far, however, the literature has not attempted to incorporate a model for it into flow simulation as there are plenty of more significant challenges to flow simulation regarding the permeability. But simulation methods are improving, which will eventually bring the effect of capillary pressure into the limelight as further improvements in accuracy are desired.

Previous work presented a 1D flow simulation model that incorporates the effects of capillary pressure on resin infusion pressure gradients. This model was supported by recent results in measuring the pressure gradients during VI processing. This work presents further characterization of material parameters to optimize the model, as well as a more robust experimental method to validate predictions for pressure profiles and capillary contributions.

The parameters to be characterized include the static/dynamic contact angle, form factor of a reinforcement, and surface tension for modern fiber-resin systems. Predictions and measurements of the capillary pressure will be used in 1D flow simulation and validated against filling experiments at slow flow speeds in VI. The ideal validation experiment would include both a digital image correlation (DIC) system to monitor bag deflection (coupled with characterization of the wet compressibility), and several pressure transducers to measure the vacuum pressure on the resin at various locations. The combination of both measurement methods allows a robust experiment to validate a 1D model for coupling compressibility and capillary pressure into filling simulation.

# NOTES

# PROCESS ANALYSIS OF HAND LAY UP METHOD BY VARIOUS EXPERIENCE PERSONS

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**Keywords**: Hand Lay-Up, FRP, Interface, Void

Hand Lay-Up (HLU) method is common molding method that can deal with various shapes according to engineer's skill. However, the quality of the composites depends on the techniques of workmen. The purpose of this study is to check the influence which the difference in use of the roller in the HLU method gives to the mechanical properties of a composite material. Then, process analysis and tensile strength testing were done in FRP specimens manufactured by persons having various experience years. In the process analysis, the number of times of a roller and a direction were mainly observed. And analysis of relationship between molding process and mechanical properties was considered. As a base material, glass cloth (570g/m2) were used. And as a resin, unsaturated polyester resin (RIGOLAC150HRBQTNW) was used. Tensile strength and elastic modulus were examined. Among subjects, 44% of difference has arisen in tensile strength. And 46 % of difference has arisen in elastic modulus. It is thought that difference of interface between resin and fiber or void is influenced. Now, relationship between molding process and mechanical properties is considered.

# NOTES

# EFFECT OF IMPREGNATION PROCESS ON INTERFACIAL AND MECHANICAL PROPERTIES OF RTM MOLDINGS

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**Keywords**: Resin Transfer Molding, Impregnation process, Interfacial properties

In the automobile industry, weight saving of car bodies is being tried in order to reduce fuel consumption. Composite materials as represented by Carbon Fiber Reinforced Plastics (CFRP), which have superior specific stiffness and strength, have been expected to be used for car body instead of metal parts. However, there are a lot of new technical problems required for mass-production of car parts with composite materials, the processes to achieve light weight of cars cannot be clarified so far. One of the reasons seems that required mechanical properties for the composite structural materials and their processes were focused on aerospace applications and these are completely different from that for auto-motive composite. In order to solve these problems, Society of Automotive Composite (SAC) was established in March 2012. Solutions of the problems are that material, molding, and structure for auto-motive composites must be designed just for automotive usage. Therefore, not only automotive company, but many material makers, molding companies also joined in SAC, and various approaches for automotive composite materials were investigated. Especially, in one of our activities, RTM (Resin Transfer Molding) method have been focused on. RTM is one of the molding process for FRP with thermoset resin. This molding method has advantages for large scale fabrication of FRP structural part with complex shape, productivity and automation process. However, mechanical properties of FRP products made by RTM method are lower than that by auto-clave method with prepreg materials.

In general, it was assumed that the characteristics of composite materials would be same if materials such as reinforcements and resin, volume fraction, surface treatment, were same. However in our previous study, mechanical properties of the composite were vastly different when they were formed by using different impregnation process. From these results, resin speed and quantities of voids in resin transfer process should be a part of reasons for strength determination. For strength of composite materials, effects of interface between fiber and matrix are relatively large. In addition to the resin transfer process, curing process to form the interface should be considered.

The purpose of this study is to clarify the mechanism of strength determination in RTM molding. Interfacial properties were investigated from the point of views of chemical and mechanical, material and processing, and experimental and modeling aspects.

## NOTES

# IN-MOULD SURFACING WITH A SILICONE MEMBRANE

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Many composite applications require a gel coated surface for cosmetic or durability reasons. The most common method of preparation is to paint or spray the mould tool, allow the coating to gel before laminating onto the tacky surface. During gelation, a proportion of the styrene (which is a major component of the unsaturated polyester resin system) is lost from the open mould tool as vapour into the workshop/environment. The Styrene Producers Association has recently recommended implementing a 20 ppm limit that ensures employee safety. A new "ultra-low styrene content spray gelcoat" is reported to have achieved an average styrene concentration of 22.3 ppm relative to 54.3 ppm for a "standard gelcoat" [1].

In-mould gel-coating with a silicone shim [2] involves placing the reinforcement material and a silicone membrane into the mould before introducing resin that permeates the reinforcement material on one side of the membrane. The mould is then opened to remove the membrane before infusing a gel coating material into the space previously occupied by the membrane.

The paper will report experiments to develop this in-mould gel-coating process for resin infusion processes using a complex double tetrahedron mould tool. Data on workplace styrene levels (average styrene concentration 0.37 ppm), surface quality measurements by DOI Wavescan and pull-off adhesion strengths will be presented.

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# NOTES

# PERMEABILITY OF SHEARED WOVEN FLAX FIBRES REINFORCEMENTS; PERMEABILITY MEASUREMENTS OF THE ORTHOTROPIC BEHAVIOUR

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**Keywords**: Permeability ; orthotropic behaviour ; sheared preforms

With the increased use of Liquid Composite Moulding (LCM) processes in the aeronautical and automotive industries, the complexity of the parts and quality requirements have increased tremendously. The development of fabric forming models and the refinement of mould filling simulations, calls for improved material models to achieve the predictions expected by the industry. Accurate permeability data of reinforcing materials is essential in order to conduct Liquid Composite Moulding Simulations and design the manufacturing process more efficiently. Permeability is predominantly a function of the reinforcement architecture and its fibre volume fraction, both of which are affected by textile deformation when used to manufacture complex 3D parts. The push for more sustainable materials either biodegradable or fully recyclable is leading the composite industry to include increasingly at bio-based reinforcements and resins.

In order to gather information on the behaviour of such reinforcements during LCM manufacturing processes, the permeability behaviour of sheared textiles was determined. The fabrics were sheared before conducting the permeability tests, simulating the textile deformation that is present when preforming textiles in 3D moulds and the effects of these deformations on the textile properties were observed.

A set of in-plane permeability experiments were conducted using a 2D radial injection permeability setup where the flow front was optically tracked. The in-plane permeability tensors of the different reinforcing materials were determined for a range of fibre volume fractions and levels of shear applied. A number of outcomes based on these results can be used for simulation.

An optical technique for measuring local fibre orientation and shear in the reinforcements was utilised and coupled with the permeability experiments conducted, ensuring that the models obtained reflected the achieved level of shear. The experiments which were conducted at strictly controlled fibre volume fractions showed that the fabric permeability is strongly dependent on the degree of shear of the reinforcements during impregnation. This study points out the necessity to take into account those orthotropic effects in impregnation of sheared reinforcements.

# NOTES

# PERMEABILITY DETERMINATION OF RESISTIVE WELDED CARBON FABRICS

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In this paper permeability determinations for a new method of processing carbon material were presented. Basic requirement was a bindered 12k plain weave and an electrical anode-to-cathode system developed by HS Weingarten.

The electrical conductivity of carbon was used to lead the power crosswise through the fibers, which activated the binder in between through thermal generation and to weld the different layers together. Through this feature it was possible to create resistive weldings with defined pressure, ampere and volts.

The welding points influenced the compaction, the fiber volume ratio and thereby the permeability of the fabrics. These variations were measured and the influence on permeability was estimated to give further recommendations for the preforming process in production.

Each sample consisted of three layers with a dimension of 290 mm x 290 mm and a fibre volume ratio of 55 %. The permeability test bench developed at the Institute of Aircraft Design worked with a radial constant pressure infusion, an optical measuring system based on Adams et al. [1] and Glycerol 85 % as injection fluid.

Following simulations with the finite element code PAM-RTM developed by ESI Group were done and the effect of resistive welding was reproduced.

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# NOTES

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