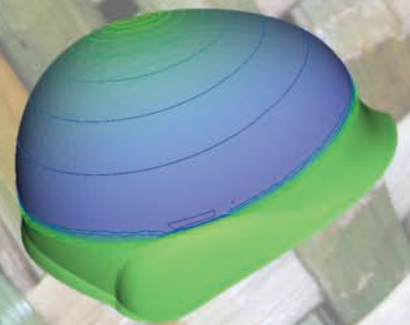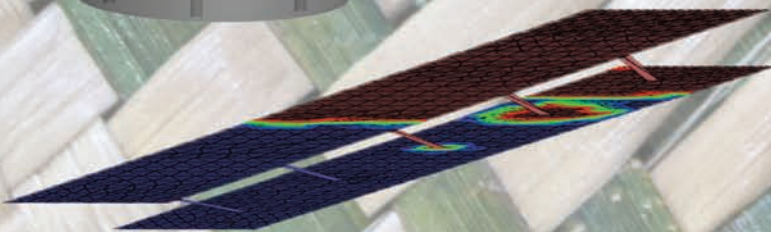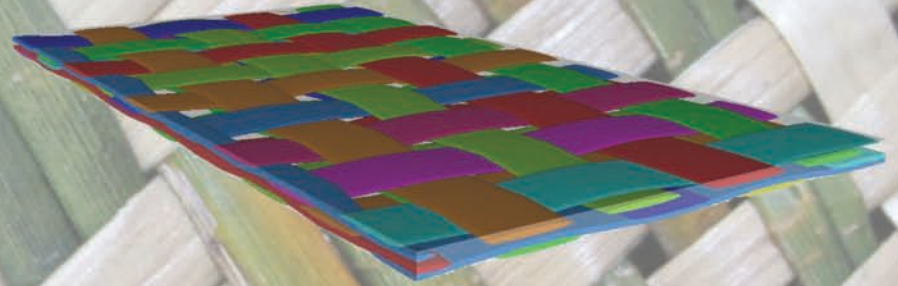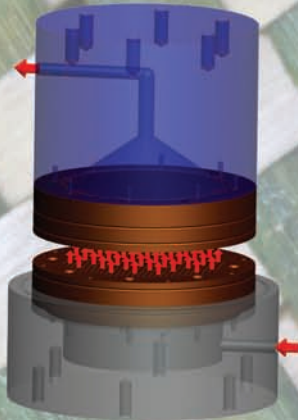# Flow Processes in Composite Materials

FPCM - 11

Auckland, New Zealand, July 2012

Program and Abstracts

Dear Colleagues,

On behalf of the Organising Committee, we would like to extend our warmest welcome to you for attending the Eleventh International Conference on Flow Processes in Composite Materials (FPCM11) in Auckland.

The conference is to be held in scenic New Zealand and we do hope you will enjoy the Downunder experience. The eleventh episode (9-12 July, 2012) of this international conference has been put together by the Centre for Advanced Composite Materials (CACM) within the Faculty of Engineering at the University of Auckland. The objective is to bring together engineers, technologists and scientists from industry, universities and research laboratories; working on various aspects related to the manufacture and processing, characterisation and evaluation of composite materials. It is envisaged that it will encourage interchange and discussion of research findings, observations and inferences within the scientific and engineering community.

FPCM11 is following on from successful meetings in Ascona, Switzerland (FPCM10, 2010), Montreal, Canada (FPCM9, 2008), Douai, France (FPCM8, 2006) and Deleware, USA (FPCM7, 2004). Following the previous successes, the FPCM11 is expected to provide high quality technical programmes related to flow processing and manufacture of composite materials.

As a modern city, Auckland - the City of Sails, is surrounded by subtropical islands, sparkling water and lush native rainforest. Auckland's unique lifestyle has been voted amongst the best in the world, with 23 regional parks, two marine reserves, 100 km of coastline, more than 500 km of walking and hiking tracks and 48 volcanic cones. Auckland provides a stunning backdrop for a myriad of activities and a vast recreational playground. With an ever-changing skyline, a pulsating waterfront and a new infusion of restaurants and bars, it has become a hub for fun and excitement. Visitors can enjoy superb Pacific Rim cuisine, fresh seafood and quality wines in a range of dining options from trendy outdoor cafes and brasseries to award-winning restaurants.

The University of Auckland, situated in this main industrial and commercial centre of New Zealand, would like to welcome all the participants of FPCM11. We aim to follow the fantastic tradition set by the predecessors and organise a pleasant, exciting and informative meeting for all the participants. We hope you enjoy your time staying in New Zealand before and after the conference.

Best wishes.

Assoc/Prof. Simon Bickerton (Co-Chair)
Dr. Piaras Kelly (Co-Chair)

Local Organising Committee

Member	Affiliation
Simon Bickerton	The University of Auckland
Piaras Kelly	The University of Auckland
Sheeja Chidambaram	The University of Auckland
Mark Battley	The University of Auckland
Debes Bhattacharyya	The University of Auckland
Raj Das	The University of Auckland
Quentin Govignon	The University of Auckland
Krishnan Jayaraman	The University of Auckland
Richard Lin	The University of Auckland
Kim Pickering	University of Waikato
Mark Staiger	University of Canterbury
Xiaowen Yuan	The University of Auckland

Technical Editors

Member	Affiliation
Peter Lescher	The University of Auckland
Quentin Govignon	The University of Auckland

International Scientific Committee

Member	Affiliation	Country
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Juan Garcia	Universitat Politècnica de València	Spain
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Andrew Long	The University of Nottingham	United Kingdom
Krishna Pillai	University of Wisconsin-Milwaukee	USA
Gerhard Ziegman	Clausthal University of Technology	Germany

Conference at a Glance

Monday 9th	
8:00	Registration
8:50	Welcome
9:00	Plenary
9:40	Permeability I [1]
11:00	Break
11:20	Permeability II [2A] · Green Composites I [2B]
12:40	Lunch
1:30	2nd Permeability Benchmark Exercise
2:30	Voids, Dual-scale, Capillary Flows [3A] · Thermoplastics I [3B]
3:50	Break
4:10	Process Modelling, Simulation I [4A] · Measurement [4B]
5:30	*Meeting of the Scientific Committee*
6:30	**Function**

Tuesday 10th	
8:40	Plenary
9:20	Processing I [5]
10:40	Break
11:00	Permeability III [6A] · Green Composites II [6B]
12:40	Lunch
1:30	**Excursion**

Wednesday 11th Industry day	
9:00	Technology transfer for Industry [7]
10:45	Break
11:15	Composites and Industry [8]
1:00	Lunch
2:00	Applications and Industry I [9]
3:40	Break
4:00	Applications and Industry II [10A] · Applications and Industry III [10B]
6:30	**Banquet (At the Pullman Hotel)**

Thursday 12th	
9:30	Process Modelling, Simulation II [11A] · Thermoplastics II [11B]
11:10	Break
11:30	Processing II [12A] · Green Composites III [12B]
12:30	Lunch
1:30	**Trip to CACM**

Auckland City at a Glance

Viaduct Bassin
America's Cup Village

Quay Street
Quay Street
Quay Street

Customs Street Wes
Fanshawe Street

Customs Street East

Lower Hobson Street
Lower Albert Street
Customs Street West
Market Place
Street East
Sturdee Street

Tyler Street
Galway Street
Galway Street
Galway Street
Tyler Street
Gore Street
Gore Street Lane

Wolfe Street
Federal Street
Mills Lane
Albert Street
Swanson Street
Wyndham Street
Queen Street
Fort Lane
Commerce Street
Fort Street
Britomart Place
Beach Road
Emily Place

Bradnor Lane
Wyndham Street
Hobson Street
Kingston Street
Swanson Street
Vulcan Lane
Shortland Street
O'Connell Street
Fields Lane
Chancery Street
Emily Place

Gorst Lane
Federal Street
Albert Street
Durham Lane
Durham Street West
High Street
Courthouse Lane
Kitchener Street
Bacon Lane
Braeside Street
Short Street
Anzac Avenue
Beach Road

Vogel Lane
Victoria Street West
Victoria Street West
Bowen Avenue
Bowen Lane
Princes Street
Waterloo Quadrant
Parliament Street
Eden Crescent

Elliot Street
Darby Street
Queen Street
Lorne Street
Albert Street
Wellesley Street East
Kitchener Street
Khartoum Place
Auckland Art Gallery
Albert Park
Princes Street
Alfred Street
Symonds Street
Charles Walton Lane
Wynyard Street
Alten Road
Churchill Street
Stanley Street

Mayoral Drive
Federal Street
Queen Street
Lorne Street
Rutland Street
Lorne Street
Mayoral Drive
Neales Lane
Wakefield Street
Saint Pauls Street
Wellesley Street East
Grafton Road
Stanley Street
Stanley Street
Tennis Lane
Nichol...

Greys Ave
Marmion Street
Waverley Street
White Street
Lyndock Street
Ardedale Street
Mount Street
Symonds Street
Wellesley Street East
Stanley Street
Auckland Domain

Scotia Place
Turner Street
Queen Street
Myers Park

500 m

Ferry Building	**1**
Pullman	**2**
Copthorne	**3**
Rendezvous Hotel	**4**
Faculty of Engineering	**5**
Bianco off Queen	**6**
Pharmacy	✚
Convenience Store	🏪
Supermarket	🛒
Sky Tower	T
Coffee Shop with wifi	☕
Auckland City Library (wifi)	📖
Britomart Train/Bus Station	🚆

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Tanghua
Tuba Squa
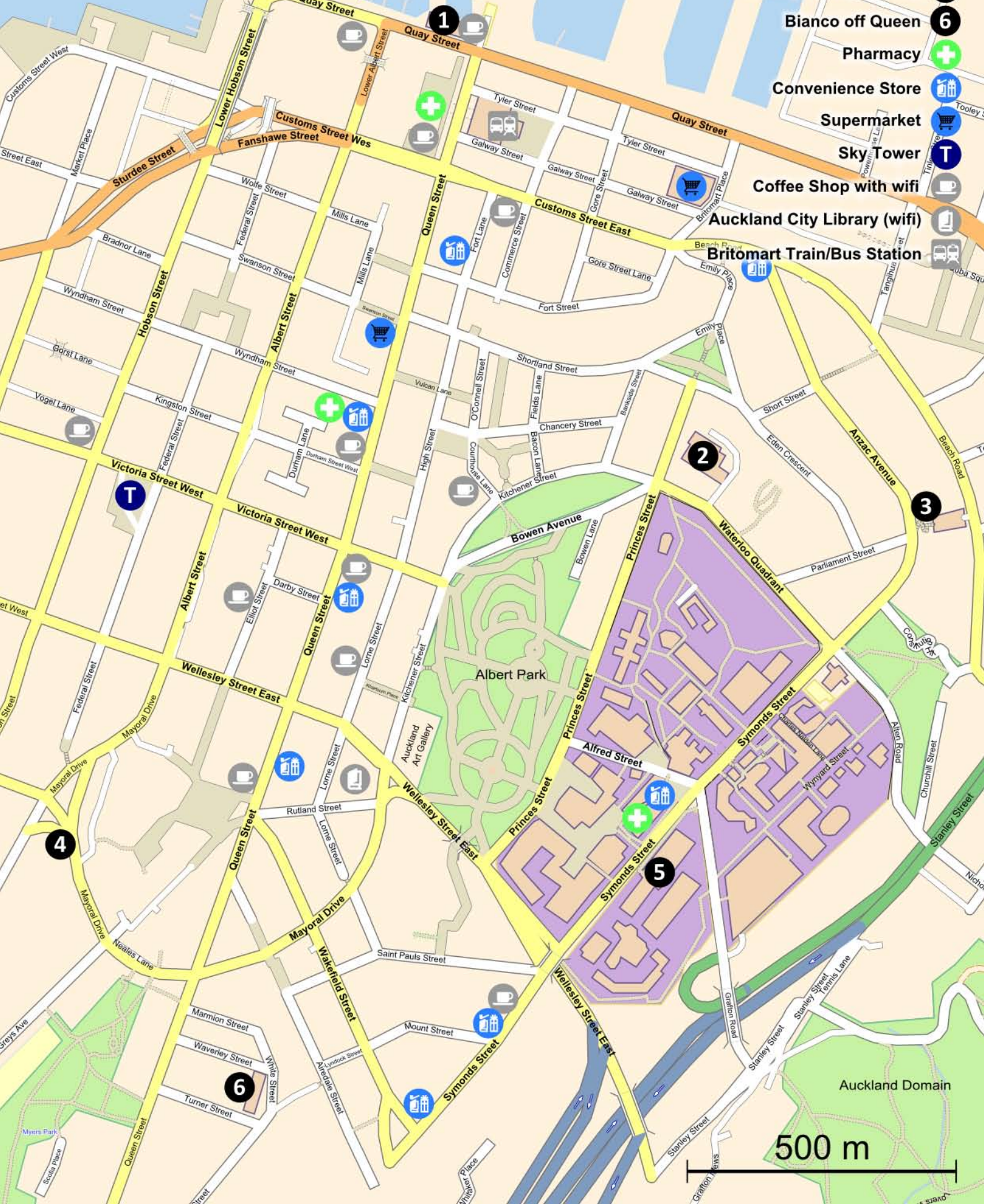
Guidelines for Presenters

ORAL PRESENTATION

A fully functional E-Lectern is available in each of the presentation rooms (1.439, 3.402 and 3.403). If you wish to use your own notebook computer, please ask the Session Helpers before the session starts. Room 3.401 is reserved as a trial room for presenters to practice and familiarize themselves with the E-lecterns. In order to ensure that the presentations run smoothly, all presenters are required to:

(i)   Fill in and submit a **Presenter Information Sheet** (included in your conference pack) to the Registration Desk at least 30 min before the session.

(ii) Supply the Session Chair with presentation files (preferably on a USB drive) no later than 10 minutes before the session starts.

(iii) Keep to the allocated presentation time:

Paper	Presentation	Discussion	Total
Plenary	35 min.	5 min.	40 min.
Industry Day (session 7)	30 min.	5 min.	35 min.
Industry Day (session 8)	20 min.	5 min.	25 min.
Regular	15 min.	5 min.	20 min.

INFORMATION FOR SESSION CHAIRPERSONS

The session chairs are expected to arrive at the presentation rooms 10 minutes before the session starts, and to check the attendance of all presenters. The registration desk will provide Presenter Information sheets via Session Helpers. Detailed chairing guidelines will be available in each of the presentation rooms.

Faculty of Engineering
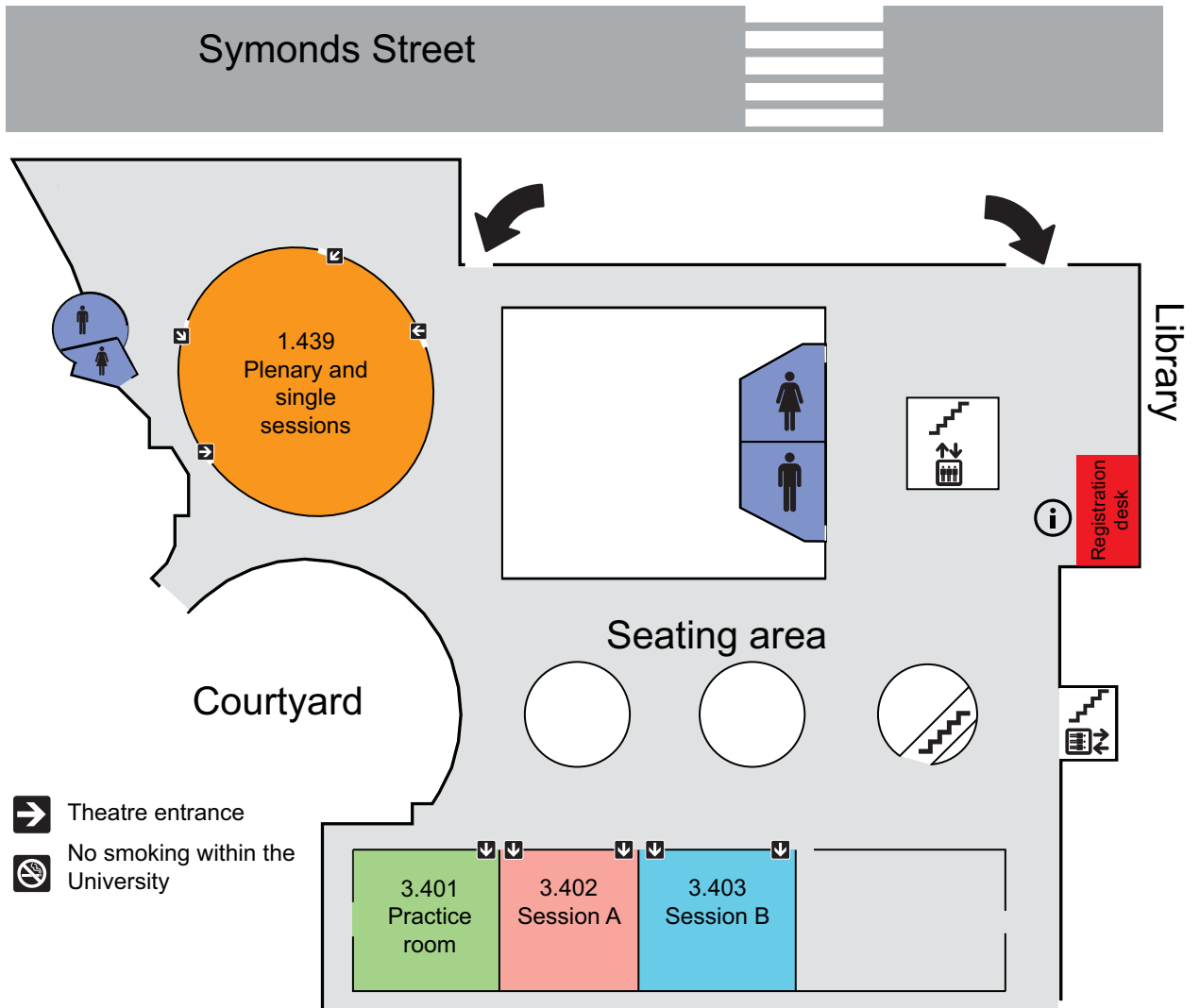
FLOORPLAN AND INTERNET ACCESS

The conference takes place on Level 4 of the Faculty of Engineering building; this is ground level when entered from Symonds Street. Wifi is available and covers this area as well as much of the wider campus; ask at the Registration desk for details.

Presentation Program

Monday July 9

	WELCOME AND PLENARY	room 1.439

8:50 – 9:00	Welcome Address	
9:00 – 9:40	Manufacturing Composite Structures for Automotive Applications: Robustness Challenges *Sébastien Comas-Cardona* **-p15**	

SESSION 1: Permeability I		room 1.439

9:40 – 10:00	A numerical method of permeability determination for RTM process simulation *Christoph Hahn, Christophe Binetruy, Roland Hinterhölzl and Klaus Drechsler* **(#66) -p15**	
10:00 – 10:20	Numerical prediction of permeability of textiles for the International Benchmark Exercise *Xuesen Zeng, Andrew C. Long and Andreas Endruweit* **(#3) -p16**	
10:20 – 10:40	Efficient generation of the voxel description of textile geometries for the computation of the permeability *Jonas De Greef, Yichen Shen, Christoph Hahn, Stepan V. Lomov, Dirk Roose, Bart Verleye and Ignaas Verpoest* **(#57) -p16**	
10:40 – 11:00	Permeability prediction of fibrous porous media with complex 3D architectures *Hai Long Liu and Wook Ryol Hwang* **(#100) -p17**	

SESSION 2A: Permeability II		room 3.402

11:20 – 11:40	Influence of textile parameters on the in-plane permeability of woven textiles *Gunnar Rieber, Jinhua Jiang, Carsten Deter, Nanliang Chen and Peter Mitschang* **(#47) -p17**	
11:40 – 12:00	Influence of binder activation and fabric design on the permeability of non-crimp carbon fabrics *Matthias Dickert, David C. Berg and Gerhard Ziegmann* **(#16) -p18**	
12:00 – 12:20	Air transport through porous media and applications to in-plane permeability measurement *Yi Hou, Sebastien Comas-Cardona, Sylvain Drapier and Christophe Binetruy* **(#79) -p18**	
12:20 – 12:40	Analysis of hysteresis phenomenon for saturated flow in LCM process *Sung Ha Kim, Sung Woong Choi, Mei Xian Li, Chung Hae Park and Woo Il Lee* **(#92) -p19**	

SESSION 2B: Natural Fibres and Green Composites I		room 3.403

11:20 – 11:40	Biobased thermoset resins and flax fibre reinforcements processed by Vacuum Assisted Resin Transfer Moulding *Jens Schuster, Quentin Govignon and Simon Bickerton* **(#1) -p19**	
11:40 – 12:00	Effect of common chemical treatments on the process kinetics and mechanical properties of flax/epoxy composites manufactured by Resin Infusion *Steven Phillips, Pei-Yu Kuo, Larry Lessard, Mohini Mohini Sain and Pascal Hubert* **(#41) -p20**	
12:00 – 12:20	Investigation of resin flow in woven (dual-scale) jute fabrics through the two-color experiment *R. Masoodi, A. Javadi and K.M. Pillai* **(#29) -p20**	
12:20 – 12:40	Influence of the type of fluid and injection conditions on the processing of natural fiber composites *Gaston M. Francucci, Analia Vazquez, Edu Ruiz and Exequiel S. Rodriguez* **(#97) -p21**	

SESSION 3A: Voids, Dual-scale and Capillary Flows		room 3.402

14:30 – 14:50	Simulation and experimental validation of the saturation in LCM processes *J.A. García, Ll. Gascón, E. Ruiz, F. Lebel and F. Trochu* **(#54) -p21**	
14:50 – 15:10	Experimental determination of void formation and transport in the RTM process *Sébastien Guéroult, Laurent Bizet and Joël Bréard* **(#27) -p22**	
15:10 – 15:30	Theoretical and experimental modelling of bubble formation with connected capillaries in Liquid Composite Moulding processes *Yanneck Wielhorski, Amine Ben Abdelwahed, Laurent Bizet and Joël Bréard* **(#53) -p22**	
15:30 – 15:50	Experimental study of capillary flows, voids formation and void migration in LCM manufacturing *E. Ruiz, F. LeBel and F. Trochu* **(#67) -p23**	

SESSION 3B: Thermoplastics I	room 3.403

14:30 – 14:50	Textile impregnation with thermoplastic resin — models and application *Richard Loendersloot, Wouter Grouve, Edwin Lamers and Sebastiaan Wijskamp* **(#25) -p23**
14:50 – 15:10	Shear characterisation of UD thermoplastic composites *S.P. Haanappel, B. Rietman and R. Akkerman* **-p24**
15:10 – 15:30	Processing of long-polymer-fiber-reinforced thermoplastic pellets by Compression Molding *Thomas Bayerl, Hristo Valchev, Erhard Natter and Peter Mitschang* **(#15) -p24**
15:30 – 15:50	Oil palm biomass reinforced polypropylene composites *Ridzuan Ramli, Rosli M. Yunus, Beg M.D.H., Rohaya Mohamed Halim, Astimar A. Aziz, Ropandi Mamat and Zawawi Ibrahim* **(#33) -p25**

SESSION 4A: Process Modelling and Simulation I	room 3.402

16:10 – 16:30	Numerical analysis of post filling flows using compliant tools *Florian Klunker, Widyanto Surjoseputro, Santiago Aranda, Daniel Beermann and Gerhard Ziegmann* **(#63) -p25**
16:30 – 16:50	A 2.5D simulation of the filling and post-filling stages of the Resin Infusion process *Quentin Govignon, Lucas Maes, Bart Verleye, Simon Bickerton and Piaras Kelly* **(#91) -p26**
16:50 – 17:10	Model development and verification of the Vacuum Infusion process for composite manufacturing *Galyna Goncharova, Mylène Deléglise, Sébastien Comas-Cardona and Christophe Binétruy* **(#11) -p26**
17:10 – 17:30	Numerical simulation of resin flow, mould deflection and reinforcement deformation in RTM Light processing *Jamie G. Timms, Simon Bickerton and Piaras A. Kelly* **(#98) -p27**

SESSION 4B: Measurement, Monitoring and Control	room 3.403

16:10 – 16:30	A multifunctional device for polymer/composite characterization *Xavier Tardif, Yasir Nawab, Nicolas Boyard, Vincent Sobotka, Pascal Casari, Frédéric Jacquemin and Didier Delaunay* **(#30) -p27**
16:30 – 16:50	Using optical fibre-based sensors to characterize resin flow and mechanical properties in LCM processes *Marc Waris, Pierre-Jacques Liotier and Sylvain Drapier* **(#78) -p28**
16:50 – 17:10	Cross-sectional monitoring of resin impregnation using an area-sensor array in an RTM process *Ryosuke Matsuzaki, Seiji Kobayashi, Akira Todoroki and Yoshihiro Mizutani* **(#90) -p28**
17:10 – 17:30	Innovative approach to track flow-front in LCM-processes through pressure sensors for in-line quality control *Claudio Di Fratta, Florian Klunker and Paolo Ermanni* **(#24) -p29**

Tuesday July 10

PLENARY	room 1.439

8:40 – 9:20	Advances in Out-Of-Autoclave Prepreg Research: From Laboratory to Large Scale Applications *Pascal Hubert* **-p29**

SESSION 5: Processing I	room 1.439

9:20 – 9:40	VARTM processing of glass fabric reinforcements coated with graphite nanoplatelets *Rehan Umer, Eric Waggy and Alfred C. Loos* **(#35) -p30**
9:40 – 10:00	Comparison between the numerical simulation program PAM-RTM and RTM-measurements on a flat plate *M. Arnold, G. Rieber, M. Wahl and P. Mitschang* **(#13) -p30**
10:00 – 10:20	Reactive flow of thermosetting resins: implications to LCM processing *Jesús Maldonado, Bryan Louis, Florian Klunker and Paolo Ermanni* **(#49) -p31**
10:20 – 10:40	Characterisation of an inorganic based resin for the liquid moulding processing of composites for intermediate temperature applications *Pascal Beneditti, Gilles Dusserre, Thierry Cutard and Julitte Huez* **(#68) -p31**

SESSION 6A: Permeability III   room 3.402

11:00 – 11:20	Value correction in the determination of transverse permeability values by using flow simulation in deformable porous media *F. Klunker, M. Danzi, T. Lämmlein, B. Louis and P. Ermanni* **(#50) -p32**
11:20 – 11:40	Influence of textile parameters on the through-the-thickness permeability of woven textiles *P. Mitschang, M. Glawe, D. Kreutz, G. Rieber and D. Becker* **(#48) -p32**
11:40 – 12:00	Optimization of 3D wetting permeability measurements *Andrew George, Anthony Pickett, Justas Sirtautas and Klaus Drechsler* **(#40) -p33**
12:00 – 12:20	Analytic method to estimate multiple permeability components from a single rectilinear experiment in Liquid Molding Processes *J. Lugo, S.G. Advani and P. Simacek* **(#60) -p33**
12:20 – 12:40	In-plane permeability characterization of fiber metal laminates made by RTM process *Iñigo Ortiz de Mendibil, René Hoto, Juan A. García, Javier Andrés, Mariasun Sarrionandia and Jon Aurrekoetxea* **(#51) -p34**

SESSION 6B: Natural Fibres and Green Composites II   room 3.403

11:00 – 11:20	Developing a novel manufacturing technique for manufacturing natural fibre reinforced thermoplastics *S.M.R. Kazmi, R. Das, S. Bickerton, Q. Govignon and K. Jayaraman* **(#101) -p34**
11:20 – 11:40	Optimum processing conditions for the manufacture of bamboo fabric-polypropylene composites *Nurul Fazita Mohammad Rawi, Krishnan Jayaraman and Debes Bhattacharyya* **(#44) -p35**
11:40 – 12:00	The manufacture and mechanical properties of aligned long harakeke fibre reinforced epoxy composites *Tan Le and K.L. Pickering* **(#36) -p35**
12:00 – 12:20	Effects of enzymatic fibre treatment on kenaf fibre reinforced recycled polypropylene composites *M.R. Islam, M.D.H. Beg and A. Gupta* **(#32) -p36**
12:20 – 12:40	An experimental estimation of liquid absorption coefficient for cellulose nano-fiber films *A. Javadi, K.M. Pillai and R. Sabo* **(#28) -p36**

Wednesday July 11

SESSION 7: Technology Transfer for Industry   room 1.439

9:00 – 9:35	Technology Transfer: from Research to Industrial Applications *Peter Mitschang, Research Director, Manufacturing Science, Institut fuer Verbundwerkstoffe GmbH, Erwin-Schroedinger-Strasse, Geb. 58, 67663 Kaiserslautern, Germany* **-p37**
9:35 – 10:10	Technology transfer in Canada: closing the gap between Science and Volume Production *Edu Ruiz, Chair on High Performance Composites (CCHP), Département de Génie Mécanique, École Polytechnique de Montréal, Montréal, Canada, H3C 3A7* **-p37**
10:10 – 10:45	Projects to programmes — Matching technology transfer approaches to company needs and resources *Mark Battley, Deputy Director; Graeme Finch, Business Development Manager, The Centre for Advanced Composite Materials, University of Auckland, New Zealand* **-p38**

SESSION 8: Composites and Industry   room 1.439

11:15 – 11:40	Nanofibres in high performance composites: commercialisation of a platform technology *Albert McGhee, General Manager, Revolution Fibres* **-p38**
11:40 – 12:05	Tooling for Racing Yachts *Susan Lake, Technical Manager, Core Builders Composites* **-p39**
12:05 – 12:30	BMW i Project: Industrialisation of the RTM Process *Simon Bickerton, Associate Professor, Centre for Advanced Composite Materials, University of Auckland, New Zealand. On secondment to BMW Group, Landshut, Germany.* **-p39**
12:30 – 13:00	Panel Discussion: Composites Manufacturing: Basic Science, Research and the Needs of Industry

SESSION 9:	Applications and Industry I	room 1.439

14:00 – 14:20	Fast impregnation of complex shapes for the manufacturing of high performance composites and its associated tooling *Clemens Dransfeld, Kunal Masania, Erich Kramer, Marcel Siegfried and Stefan Klauser* **(#2)** **-p40**
14:20 – 14:40	Numerical and experimental study of the infusion process for large scale industrial parts *Romain Agogué, Pierre Beauchêne, Jérémy Mazzolini and Julien Valette* **(#19)** **-p40**
14:40 – 15:00	Resin flow simulation based on advanced reinforcement geometry modelling from yarn-scale to component-scale *Andreas Endruweit, Frank Gommer, Joel Hutchinson, Spiridon Koutsonas, Andrew C. Long, Peter Schubel, Xueliang Xiao and Xuesen Zeng* **(#12)** **-p41**
15:00 – 15:20	Online process monitoring systems — benchmark and test study *Reinhold Meier, Swen Zaremba, Florian Springl, Klaus Drechsler, Fabrice Gaille and Christian Weimer* **(#8)** **-p41**
15:20 – 15:40	In-mould gel-coating for RTM and RIFT *John Summmerscales* **(#76)** **-p42**

SESSION 10A:	Applications and Industry II	room 3.402

16:00 – 16:20	Out-of-autoclave processing of ribbed parts: technical, economic and environmental assessment *Rémy Teuscher, Robert. A. Witik, Amaël Cohades and Véronique Michaud* **(#37)** **-p42**
16:20 – 16:40	Modelling the internal core pressure during cure of out-of-autoclave honeycomb panels *James Kratz and Pascal Hubert* **(#34)** **-p43**
16:40 – 17:00	The effect of out-time and cure cycle on the consolidation of out-of-autoclave prepregs *Timotei Centea, James Kratz and Pascal Hubert* **(#42)** **-p43**
17:00 – 17:20	Investigation of co-LCM process and the co-cured laminar interface of carbon fiber composites *Xuqiang Ma, Yizhuo Gu, Min Li, Yanxia Li and Zuoguang Zhang* **(#83)** **-p44**

SESSION 10B:	Applications and Industry III	room 3.403

16:00 – 16:20	Injection of a complex preform by RTM: Optimisation of a mould design and process parameters *R. Agogue, P. Ouagne, D. Soulat, C.H. Park, J. Breard and D. Zanelli* **(#43)** **-p44**
16:20 – 16:40	Variability of fibrous materials: experimental and theoretical study *F. Zhang, S. Comas-Cardona and C. Binetruy* **(#17)** **-p45**
16:40 – 17:00	Multi-component LCM processing for aeronautical structural applications — the influence of deflection in metering and homogenization *Florian Springl, Patrik Welz, Swen Zaremba, Christian Weimer and Klaus Drechsler* **(#6)** **-p45**

Thursday July 12

SESSION 11A:	Process Modelling and Simulation II	room 3.402

9:30 – 9:50	Uncertainty quantification in Liquid Composite Moulding processes *Bart Verleye, Dirk Nuyens, Andrew Walbran and Ming Gan* **(#58)** **-p46**
9:50 – 10:10	Neural networks versus Kriging, surrogate models for LCM process optimization *Abhishek Gupta, Piaras Kelly, Matthias Ehrgott and Simon Bickerton* **(#14)** **-p46**
10:10 – 10:30	Numerical study on consolidation process of T-stiffened skin in autoclave *Yanxia Li, Min Li, Yizhuo Gu and Zuoguang Zhang* **(#84)** **-p47**
10:30 – 10:50	Modeling the constitutive response of an anisotropic dual-scale flow *Mohammad Rouhi, Maciej Wysocki and Ragnar Larsson* **(#4)** **-p47**
10:50 – 11:10	Monolithic versus decoupled approach to couple Stokes/Darcy flows in extreme regimes for LCM process modelling *L. Abou Orm, R. Troian, J. Bruchon, N. Moulin, P.-J. Liotier and S. Drapier* **(#80)** **-p48**

SESSION 11B: Thermoplastics II   room 3.403

9:30 – 9:50	Pultrusion system for continuous fiber reinforced thermoplastic composite *Anin Memon, Toshihiro Motochika, Daisuke Hatano, Asami Nakai and Akio Ohtani* **(#88)** **-p48**
9:50 – 10:10	Modelling of laser welding process on thermoplastic composites *Benoit Cosson, Mylène Deléglise, Wolfgang Knapp, Philippe Castaing and Christophe Binétruy* **(#22) -p49**
10:10 – 10:30	Influence of processing conditions on the permeability of microfibril-reinforced composites *Sylvester Tan, Arcot A. Somashekar and Debes Bhattacharyya* **(#102) -p49**
10:30 – 10:50	Synthesis and characterization of multi-walled carbon nanotube reinforced Poly Ether Ether Ketone composite *Nikhil Shaun Mepurathu, Gavin Lawes, Akila Deeghayu Kumarasiri and Susil K. Putatunda* **(#23) -p50**
10:50 – 11:10	Elastic properties of short fibres reinforced polymers in the vicinity of a weld line *Gilles Dusserre* **(#69) -p50**

SESSION 12A: Processing II   room 3.402

11:30 – 11:50	Flow and heat transfer inside an autoclave *N.E. Jimmy Olsson, T. Staffan Lundström, L-G. Westerberg and Tonny Nyman* **(#95) -p51**
11:50 – 12:10	Preparation and optimisation of modified DGEBA-based epoxy resin as a self-healing composite matrix *E.H. Lim and K.L. Pickering* **(#18) -p51**
12:10 – 12:30	Compaction response and air permeability characterisation of out-of-autoclave prepreg materials *Christopher M.D. Hickey, Jamie. G. Timms and Simon Bickerton* **(#103) -p52**

SESSION 12B: Natural Fibres and Green Composites III   room 3.403

11:30 – 11:50	Fiber orientation observation of jute fiber filled injection moldings *Yuqiu Yang, Putinun Uawongsuwan, Cuntao Wang, Masuo Murakami, Hiroyuki Hamada and Asami Nakai* **(#86) -p52**
11:50 – 12:10	Optimization of the manufacturing of twill bamboo fabric reinforced polypropylene hybrid composites laminates *Nurul Mahmud Zuhudi, Xiaowen Yuan and Krishnan Jayaraman* **(#45) -p53**
12:10 – 12:30	Effect of ultrasonic treatment on the compatibility and mechanical properties of oil palm empty fruit bunch (EFB) fiber reinforced polylactic acid composites *A.K.M.M. Alam, M.D.H. Beg, D.M.R. Prasad and R. M. Yunus* **(#31) -p53**

Presentation Abstracts

[PLENARY 1] **Manufacturing Composite Structures for Automotive Applications: Robustness Challenges**

Sébastien Comas-Cardona

Gas emission reduction targeted by state regulators is driving car mass reduction. Replacing metallic structural parts by composites ones would lead to a substantial mass saving. Solutions relying on fiber reinforced thermoset or thermoplastic composites have to be assessed. The automotive industry seeks manufacturing solutions which can yield composite parts within minutes at competitive costs. Manufacturing high quality composites at such rates raises several modeling and simulation challenges. Among them, process robustness has to be evaluated to ensure quality and competitiveness of composite solutions. Once the physical phenomena, involved in manufacturing, are identified, coupled and solved, their variability has to be characterized. Then the variability in process and material parameters has to be propagated to estimate robustness.

Monday, 9:00 – 9:40, room 1.439

SESSION [1] **A numerical method of permeability determination for RTM process simulation**

Christoph Hahn, Christophe Binetruy, Roland Hinterhölzl and Klaus Drechsler

Resin injection such as resin transfer molding (RTM) is commonly applied in industry for serial production of composite components. RTM process simulation enables prediction of process parameters that are essential for component and tool design. As for all simulations where material behavior is modeled, validated material properties are indispensable for realistic simulations. Currently, material properties have to be determined experimentally which is costly and time consuming. Furthermore, standardized methods for permeability testing are not yet available. This paper presents an approach to determine permeability numerically for carbon fiber fabrics. The most important benefit is the speed-up compared to experimental testing. With fast material characterization, process simulation can be employed in the early design phase of a component. An optimal trade-off between component quality and producibility can be reached without extensive prototyping and testing. The approach is exemplarily applied for a biaxial non-crimped fabric. The way forward is as follows: Information that is inherent in digital images of scanned fabrics is extracted using image analysis. The results are taken as input data for textile modeling with WiseTex. Then, FlowTex is employed in order to determine permeability. A self-developed Matlab® routine performs the image analysis, interacts with the abovementioned tools and finally writes a material card for direct use in RTM simulation. In the paper, numerical results are correlated to experimental results in order to show the quality in predicting material behavior.

Monday, 9:40 – 10:00, room 1.439

SESSION [1] **Numerical prediction of permeability of textiles for the International Benchmark Exercise**

Xuesen Zeng, Andrew C. Long and Andreas Endruweit

A recent international benchmark exercise compared in-plane permeability data for two woven reinforcement fabrics and determined experimentally using 16 different procedures. The results showed a scatter of one order of magnitude in principal permeability values, which was attributed to the difference in procedures implemented by the participants in the study and to operator induced effects, in particular related to specimen preparation and execution of the experiments. A second round of the benchmark exercise is under way, aiming at standardisation of experimental methods. Numerical permeability prediction can provide complementary validation data to the new benchmark exercise. A unit cell based Computational Fluid Dynamics (CFD) model for permeability prediction is presented in this study. The first step was to scan the fabrics at the same compression state as for permeability measurement using micro-Computed Tomography (μ-CT). The obtained 3D image data were then evaluated to characterise the actual fabric geometry. The second step was more predictive in that the geometric model was generated based on a set of approximate rules as defined in the textile scheme, TexGen. Comparison of the CFD results from TexGen models with those from experiments indicates the level of idealisation that is acceptable for permeability modelling

Monday, 10:00 – 10:20, room 1.439

SESSION [1] **Efficient generation of the voxel description of textile geometries for the computation of the permeability**

Jonas De Greef, Yichen Shen, Christoph Hahn, Stepan V. Lomov, Dirk Roose, Bart Verleye and Ignaas Verpoest

For the accurate simulation of Liquid Composite Moulding processes, the input of the permeability of the preform is required. The permeability of a textile can be obtained experimentally, or can be computed. To compute the permeability, the software FlowTex was developed at the KU Leuven, as part of the textile modelling software package WiseTex. FlowTex transforms the vector description of the textile models into a voxel description, which is input for the finite difference flow solver. In this paper we present the implementation of the flooding algorithm to make this transformation more efficient. Validation and convergence studies, both for the voxelisation as for the permeability computation are presented

Monday, 10:20 – 10:40, room 1.439

SESSION [1] **Permeability prediction of fibrous porous media with complex 3D architectures**
Hai Long Liu and Wook Ryol Hwang

We present a new three-dimensional finite element technique to solve flows in a representative porous volume with fibrous microstructures, which employs a fictitious domain method to deal with immersed microstructures and a mortar-element method to satisfy rigorously the tri-periodic boundary condition for the representative volume element. Through the extensive numerical simulations for various fiber and fabric architectures, we investigate the relationship between the permeability and fiber architectures in order to seek a reasonable approximation method in estimating the permeability of complex architectures. Specifically we discuss the applicability and limitation of a macroscopic permeability averaging rule in estimating those of complex microstructures, using the information of simple structural building blocks. We then investigate the Kozeny constants of various microstructures for a wide range of the fiber volume fraction, which may facilitate simple permeability estimation of complex 3D porous structures using the Kozeny-Carman model.

Monday, 10:40 – 11:00, room 1.439

SESSION [2A] **Influence of textile parameters on the in-plane permeability of woven textiles**
Gunnar Rieber, Jinhua Jiang, Carsten Deter, Nanliang Chen and Peter Mitschang

Product parameters of woven textiles like weave, linear density, yarn density and crimp determine the permeability, infiltration, and use as reinforcement textile in a polymer composite structure. Nevertheless, attempts to link these parameters to the permeability of woven textiles are rare. In the empirical part of this study, 19 woven glass fiber textiles were selected to determine the effect of the weave, linear density, yarn density, and crimp on in-plane permeability. Further influencing parameters, like the finish and the filament diameter, have been left constant. The measurements have been conducted on a stiff two-sided aluminum tool with eight linear capacitive sensors. The anisotropic flow behavior of isotropically built up textiles is explained by using the crimp in the warp and weft yarns. It was observed that a higher difference between the crimp in the warp and weft yarns resulted in a higher difference between the K1- and K2-permeability data. A pattern was found to divide textiles into dense and open weave textiles to characterize the permeability behaviour. A generally valid relationship was found between the weaving density (defined as the product of linear density and yarn density) of a textile and the slope of the permeability-fiber volume fraction curve. In a comparison of three identically built up twill and satin weave textiles, it was found that the K2 permeability of twill weave textiles is significantly lower compared to the K1 permeability, meaning that twill weave textiles are more anisotropic. The results of this study allow the selection and tailoring of woven textiles with specific, for example very low or isotropic, permeabilities.

Monday, 11:20 – 11:40, room 3.402

SESSION [2A] **Influence of binder activation and fabric design on the permeability of non-crimp carbon fabrics**

Matthias Dickert, David C. Berg and Gerhard Ziegmann

In this study we present results of permeability measurements. Different binder types (epoxy-based powder, acrylate-styrene co-polymer powder and co-polyamide-based veils) were applied to non-crimp carbon fiber fabrics in varying amounts. Depending on the activation parameters used, different modes of interaction of binder and fabric could be observed. High press temperatures and long pressing times lead to capillary flow of the binder. In this study lower temperatures and shorter pressing times are used to solely deform the binder particles by compaction forces, leaving them on the roving surface. In one fabric we find both a permeability increase as well as a decrease depending on the binder types. A second type of fabric only yields permeability decrease for increasing binder amounts. From these observations we conclude that in addition to binder type and activation parameters fabric parameters also impact the binder's influence on permeability.

Monday, 11:40 – 12:00, room 3.402

SESSION [2A] **Air transport through porous media and applications to in-plane permeability measurement**

Yi Hou, Sebastien Comas-Cardona, Sylvain Drapier and Christophe Binetruy

Permeability of a fibrous reinforcement is an important physical parameter in Liquid Composite Molding (LCM). A great amount of effort has been spent on measuring such material property. Most of the techniques employed rely on liquid injection experiments. However permeability measurement using air instead of a liquid can provide a cleaner and faster measurement with reusable fabrics. This paper introduces a methodology to measure in-plane permeability of fibrous media using a transient one dimensional air flow. The method, based on the measurement of gas pressure at the boundaries throughout the transient flow, avoids usage of a gas flow meter and offers a way to study the gas transport within fibrous media. The permeability, only depending on the porous structure, is determined by inverse method, fitting the simulation results to the experimental data. Several models are built to describe air transport in different flow regimes. Results obtained by liquid injection and transient air flow match well in Darcy's regime. The deviation from Darcy's law caused by air sliding effect is analyzed.

Monday, 12:00 – 12:20, room 3.402

SESSION [2A] Analysis of hysteresis phenomenon for saturated flow in LCM process
Sung Ha Kim, Sung Woong Choi, Mei Xian Li, Chung Hae Park and Woo Il Lee

Liquid Composite Molding (LCM) such as Resin Transfer Molding (RTM) is becoming one of the promising processes in the composite manufacturing process due to their versatility, economic advantages among other merits. To understand the flow behavior in LCM process, it is important to observe the permeability characteristics. Tow deformation and pressure gradient behavior through the flow were observed with different volume flow rates and fluid viscosities to characterize the relation between the volume flow and permeability regarded to tow deformation. Permeability was varied with the volume flow, and it showed hysteresis when increasing and decreasing the volume flow rate due to tow deformation. The intensity of hysteresis was changed by fluid viscosity which affects tow deformation.

Monday, 12:20 – 12:40, room 3.402

SESSION [2B] Biobased thermoset resins and flax fibre reinforcements processed by Vacuum Assisted Resin Transfer Moulding
Jens Schuster, Quentin Govignon and Simon Bickerton

Biocomposite panels consisting of biobased thermoset resins (EP, UP, and tannin) and flax fibre reinforcements were produced using the vacuum assisted resin transfer moulding process. Panels based on a conventional chemical-based resin matrix were also produced, and investigated comparatively. Rheometric analyses were performed to evaluate the suitability of these resins for liquid composite moulding. Tensile, shear, and impact-bending tests have been carried out to assess the quality and mechanical performance of manufactured laminates. The impregnation quality was assessed by means of ultrasonic-C-scanning and microscopy. It turned out that the properties of the biobased composite panels made of biobased epoxy resin and a biobased UP-resin from the company Nuplex in New Zealand were only slightly inferior to those produced with a conventional epoxy resin. A biobased UP-resin from the company USSC in the USA developed voids during curing. A tannin based resin containing of formaldehyde was not processable.

Monday, 11:20 – 11:40, room 3.403

SESSION [2B] **Effect of common chemical treatments on the process kinetics and mechanical properties of flax/epoxy composites manufactured by Resin Infusion**

Steven Phillips, Pei-Yu Kuo, Larry Lessard, Mohini Mohini Sain and Pascal Hubert

The chemical treatment of cellulose-based fibres such as flax is an important step in improving their adhesion with common resin systems in the production of bio-based composites. However, the implications of these treatments on processing behaviour are not yet fully understood. This study investigated the effect of common chemical treatments on the flow and compaction behavior of woven flax fabrics during the resin infusion process. Woven flax fabrics were treated by acetone, alkaline, silane and diluted epoxy based on previously proposed methods. The treated fabrics were then infused with resin during which the evolution of flow front and preform thickness was monitored. The cured laminates were finally subjected to flexural testing, edgewise parallel Charpy impact and void analysis by optical microscopy. The results suggest that the studied chemical treatments increased the effective permeability of the flax fabrics. This was most apparent for the alkaline treatment which showed a 50% increase in effective permeability mostly due to an increase in porosity caused by fibre swelling. The latter observation suggested that the tension in the fibres during alkaline treatment is an important parameter in the context of composite processing. The results from flexural testing demonstrated the negative effect of voids on flexural properties. On the other hand, results from Charpy test revealed no clear trends. For the treatments studied, the diluted epoxy provided the best balance between mechanical properties and process-ability.

Monday, 11:40 – 12:00, room 3.403

SESSION [2B] **Investigation of resin flow in woven (dual-scale) jute fabrics through the two-color experiment**

R. Masoodi, A. Javadi and K.M. Pillai

The current breed of natural-fiber based polymer composites offer 'green' alternatives for the automotive and other engineering applications. Jute, one of the most useful and inexpensive of all the natural fibers, is usually available as woven fabrics, often in the form of gunny sacks. Many polymer composite parts are made by the liquid composite molding (LCM) process where accurate mold-filling simulations are often employed to optimize mold design. However, the use of natural fiber preforms made from woven jute fabrics adds several hitherto unexplored complexities to the LCM mold-filling physics. One such complexity arises from the flow of resin in a dual-scale porous medium created by woven fabrics in LCM molds. In this paper, we study the effect of the dual-scale architecture on resin flow in LCM using a two-color experiment. During the making of a jute part using epoxy resin, injection of a colored resin is followed by the injection of resin of another color. Trapping of the earlier-injected resin inside fiber tows of the jute fabric is clearly demonstrated through this experiment. Such a result, also seen in the conventional glass fabrics, has tremendous implications as far as modeling of temperature and cure during LCM mold-filling in concerned.

Monday, 12:00 – 12:20, room 3.403

SESSION [2B] Influence of the type of fluid and injection conditions on the processing of natural fiber composites

Gaston M. Francucci, Analia Vazquez, Edu Ruiz and Exequiel S. Rodriguez

In composites manufacturing, proper impregnation of the fibrous reinforcement is key for obtaining consistent mechanical properties of the components. The capillary flow taking place during resin injection is an important driving force for the infiltration of the fibers. Capillary flow is also a main mechanism on the void formation during resin injection. In the case of natural fibers, important capillary effects appear due to the hollow structure of the fibers, small diameter and molecular polarity. In a previous work presented at FPCM10, the authors have shown the characterization of the capillary effects arising during the infiltration of natural fiber preforms. In this work, the effect of the type of fluid used for the permeability test on the unsaturated permeability value was estimated and related to the capillary effects developed during the infiltration. In addition, the permeability of the fabrics was measured under different injection conditions, constant flow rate and constant pressure, and the differences observed could be explained taking into account the capillary effects developed in each case. Finally, the capillary pressure obtained in the constant pressure experiments was used to correct the applied pressure gradient in the transient unsaturated permeability tests and thus a corrected value of permeability independent of the tests fluid was obtained. The results obtained suggested that the processing conditions, such as type of fluid, injection method and flow velocity could affect significantly the measurements of unsaturated permeability.

Monday, 12:20 – 12:40, room 3.403

SESSION [3A] Simulation and experimental validation of the saturation in LCM processes

J.A. García, Ll. Gascón, E. Ruiz, F. Lebel and F. Trochu

In a previous work, equations that describe the LCM filling process with void formation were introduced. These equations are based on a two phase flow model and lead to a coupled system of a nonlinear advection-diffusion equation for saturation and an elliptic equation for pressure and velocity. This model introduces the relative permeability as a function of saturation and a modified equation for the saturation as a non-linear advection-diffusion equation including viscous and capillary phenomena. The hyperbolic nature of the saturation equation and its strong coupling through relative permeability represent a challenging numerical issue. Many numerical methods used to solve hyperbolic equations suffer from nonphysical oscillations and numerical dispersion. Usually, two terms contribute to smooth the numerical flow front position: one is related to the source term, and the other is a purely mathematical term introduced by the discretization scheme. The last effect can be reduced by using higher order numerical scheme to solve the nonlinear equation. The technique used in this paper for solving the saturation equation is based on an essentially non-oscillatory fixed mesh FEM approach. A detailed analysis for different relative permeability models combined with saturation equation is performed to assess the saturation profiles. To validate the proposed model, FEM predictions were compared with experimental data obtained on a glass RTM mold under controlled manufacturing conditions. Injections were carried out at different flow rates and saturation and saturation as measured as a function of time during impregnation. Measured saturation profiles in time were then compared to those numerically predicted.

Monday, 14:30 – 14:50, room 3.402

SESSION [3A] **Experimental determination of void formation and transport in the RTM process**
Sébastien Guéroult, Laurent Bizet and Joël Bréard

The RTM (Resin Transfer Molding) process is a technological solution that enables the production of high quality structural composites. Defects in the form of voids are formed during the injection process. These defects are detrimental to the final mechanical properties of the composite materials. Thus, it is important to control their formation and transport. Depending on their relative size and location within the preform, these voids can be classified in two categories and they are named microvoids and macrovoids. In this study, all the injections were carried out longitudinally in an experimental device designed to replicate the conditions of an RTM process. Two model liquids were chosen to replace the thermosetting resins that are traditionally used in the injection processes. A network of sensors dynamically measured the evolution of the saturation in the mould. A homemade conductivity sensor was used for conductive liquids in combination with insulating material such as glass fibre preforms. Alternatively, a homemade permittivity sensor was developed for insulating materials such as unidirectional glass fibres and silicone oil. The evolution of the saturation profiles as a function of time and place was measured at constant pressure and flow rate. Both techniques generate data describing the saturation and the void formation and transportation. The results are consistent with models from the literature that describe the macrovoids for low capillary numbers, the microvoids for high capillary numbers and a minimum of voids for an optimal capillary number.

Monday, 14:50 – 15:10, room 3.402

SESSION [3A] **Theoretical and experimental modelling of bubble formation with connected capillaries in Liquid Composite Moulding processes**
Yanneck Wielhorski, Amine Ben Abdelwahed, Laurent Bizet and Joël Bréard

The void prediction in LCM processes sparks off interest within the composite material industry because it is a significant issue to keep the expected mechanical properties. The liquid properties, the preform geometry and the flow conditions impact the quantity of void entrapped inside the final product. The complex geometry of the reinforcement due to the arrangement of the bundles and the fibres is a key point to understand and quantify this phenomenon. This paper deals with both simple model networks which can occur inside a fabric representing connected capillaries, so-called "Pore Doublet Model (PDM)". A first is considering two capillaries converging on a node (T-junction) and a second is representing two capillaries interconnected with a supplying principle. These configurations can affect locally the evolution of flow fronts. First, experiments of bubble formed in a T-junction device have been performed and studied. Then a theoretical approach was proposed to forecast microvoid and macrovoid formation, by taking into account a supplying principle and arranged Washburn equation in forced filling.

Monday, 15:10 – 15:30, room 3.402

SESSION [3A] **Experimental study of capillary flows, voids formation and void migration in LCM manufacturing**
E. Ruiz, F. LeBel and F. Trochu

Engineered fibrous reinforcements commonly used in LCM processes behave as a dual scale porous media with a macroscopic porosity defined between the tows and a microscopic porosity between the filaments inside the fiber tows. This dual scale porosity is a result of the stitching/weaving process of the fabric. On a microscopic scale, capillary flows developed during impregnation of fiber tows play a major role on the quality of composites made by resin injection through fibrous reinforcements. In this work, a study of dual scale fabric saturation was carried out in order to understand the mechanisms that govern the impregnation of fibrous reinforcements and the formation of porosities in LCM manufacturing. The experimental approaches of this research are based on a new visible light transmission (VLT) method and on RTM injections in a glass mold. This VLT method was based on fundamentals of optics and it allows a better understanding of the mechanisms of void formation and transport in dual scale fibrous reinforcements. The result of this advanced monitoring tool for fibrous reinforcement saturation was to propose an impregnation model linking the formation of the macroscopic and microscopic porosities to the capillary number. Finally, a thermosetting resin was used to carry out RTM injections at constant flow rate in order to validate the proposed impregnation model as well as the predictions of optimal injection conditions obtained by the capillary rise experiments with the same resin and the same fibrous reinforcement.

Monday, 15:30 – 15:50, room 3.402

SESSION [3B] **Textile impregnation with thermoplastic resin — models and application**
Richard Loendersloot, Wouter Grouve, Edwin Lamers and Sebastiaan Wijskamp

One of the key issues of the development of cost-effective thermoplastic composites for the aerospace industry is the process quality control. A complete, void free impregnation of the textile reinforcement by the thermoplastic resin is an important measure of the quality of composites. The introduction of new, more thermal resistant and tougher polymers is accompanied by a large number of trial and error cycles to optimise the production process, since the polymer grade strongly influences the processing conditions. Therefore, a study on the impregnation is performed. Thermoplastic manufacturing processes are often based on pressure driven, transverse impregnation, that can be described as a transient, non-isothermal flow of a non-Newtonian fluid, where a dual scale porosity is assumed for the reinforcement's internal geometry. Meso- and micro scale models of isothermal flow revealed a limited sensitivity to the process conditions at the bundle scale for high pressure processes such as plate pressing, with an increasing sensitivity for lower pressures as apply for autoclave processes. The process conditions are significant for the quality of impregnation at filament scale. Specific combinations of pressure, viscosity and bundle compressibility can lead to void formation inside the bundles, as confirmed by microscopic analysis. The methodology developed has been translated to a ready-to-use design tool for the implementation of new polymers.

Monday, 14:30 – 14:50, room 3.403

SESSION [3B] **Shear characterisation of UD thermoplastic composites**
S.P. Haanappel, B. Rietman and R. Akkerman

Intra-ply shear is one of the main mechanisms to accumulate deformations in thermoplastic composites forming processes. In this paper a shear characterisation method for unidirectionally (UD) reinforced thermoplastics in their molten configuration is presented. Bar-like specimens made from UD carbon PEEK material are subjected to oscillating torsional loads. By utilising linear visco-elastic theory, the small strain oscillatory responses are translated to storage and loss shear moduli. The frequency dependent moduli are subsequently translated to the transient domain and show a close-to elastic response for the considered instantaneous strain rates. The application of such characterisation data is demonstrated by modelling the stamp forming process of a complex shaped product with the aid of the finite element method. The process considered deals with an initially flat quasi-isotropic laminate consisting of eight plies, which is formed at high temperatures. Predicted intra-ply shear strains are compared with those measured by photogrammetry in a real formed part. Predicted and measured shear strain distributions and their magnitudes were in good agreement. Moreover, critical regions in which small wrinkles develop were indeed indicated by the forming predictions.

Monday, 14:50 – 15:10, room 3.403

SESSION [3B] **Processing of long-polymer-fiber-reinforced thermoplastic pellets by Compression Molding**
Thomas Bayerl, Hristo Valchev, Erhard Natter and Peter Mitschang

Polymer-polymer materials consist of a matrix and a reinforcement which originate from the same thermoplastic family. Recent research activities concentrate on the manufacturing of semi-finished polymer-polymer materials in other shapes than the commercially available tapes and sheet-like semi-finished products. A pellet-like form allows the possibility of processing the polymer-polymer material by injection and compression molding. The component design variety offered by these processes is almost unlimited. Nevertheless, the thermoplastic reinforcement is vulnerable to excessive heat. This problem has not been addressed yet since it does not appear with the use of inorganic reinforcements such as glass and carbon fibers. This study deals with the processing of long-polymer-fiber reinforced thermoplastics, in this case polypropylene-polyethylene terephthalate (PP-PET) and a self-reinforced polyethylene terephthalate (PET-PET), by extrusion for compression molding applications. The influence of extruder temperature on fiber reinforcement and processability is discussed by means of built-in-press rheometry. The impact of the heating process on mechanical properties, such as tensile strength, Young's modulus, and impact strength, is also addressed. The results revealed that the use of a common long fiber reinforced thermoplastic (LFT) process chain is adaptable for the newly developed polymer-polymer material in order to manufacture a complex shaped component. The flow characteristics of the material as well as the preservation of the polymer reinforcement can be handled by means of accurate temperature control.

Monday, 15:10 – 15:30, room 3.403

SESSION [3B] **Oil palm biomass reinforced polypropylene composites**
Ridzuan Ramli, Rosli M. Yunus, Beg M.D.H., Rohaya Mohamed Halim, Astimar A. Aziz, Ropandi Mamat and Zawawi Ibrahim

Oil palm empty fruit bunch (EFB) fibre and oil palm clinker (OPC) reinforced polypropylene (PP) composites were prepared by the melt-cast technique. Grinded EFB fibre and crushed OPC was compounded separately into polypropylene using a twin-screw compounder, with fiber contents of 10–40 wt% as well as without coupling agent and with 2–4 wt% coupling agent. The extrudates were then injection moulded to fabricate composites. The composites were characterized by mechanical, melt flow index (MFI), surface morphological and thermal tests. The mixing torque for PP and PP/EFB composites was found to be very close, whereas the torque of PP/OPC shows higher value than that of PP/EFB. The MFI of PP drops from 8 g/10 min to 5.2 for EFB/PP and to 4.2 for OPC/PP composites with increasing fibre content. Interestingly, the heat distortion temperature increases for the composites as compared to the pure PP. Incorporation of coupling agent in the composite exhibits better mechanical and thermal performances than without coupling agent due to better interfacial adhesion between fibers and PP matrix.

Monday, 15:30 – 15:50, room 3.403

SESSION [4A] **Numerical analysis of post filling flows using compliant tools**
Florian Klunker, Widyanto Surjoseputro, Santiago Aranda, Daniel Beermann and Gerhard Ziegmann

A methodology for a fully coupled post filling flow is applied. This methodology can be extended in future works to different processes like the impregnation of textiles in vacuum assisted resin infusion (VARI), compression RTM or similar processes, where the flow is affected by the transversal deformation of the textile. As in this paper the post filling flow is addressed, the results can be used e.g. for the post filling phase in VARI or for the compression phase in prepreg processes. The results indicate that in unconstrained 1D-flows an up-scaling rule can be applied, meaning by knowing the post-filling flow for small samples, the result in larger structures can be predicted by simple rules: If the textile shows elastic properties, the ratio of processing times for reaching a certain post-filling stage (final thickness, pressure distribution) is increasing with the square of the ratio of part length.

Monday, 16:10 – 16:30, room 3.402

SESSION [4A] A 2.5D simulation of the filling and post-filling stages of the Resin Infusion process

Quentin Govignon, Lucas Maes, Bart Verleye, Simon Bickerton and Piaras Kelly

The Resin Infusion process (RI, also known as VARTM) is a subclass of the Liquid Composite Moulding (LCM) collective, which is increasingly applied in industry. As opposed to the other LCM processes, RI utilises only one rigid mould half, the upper mould half of the mould being a flexible plastic bag. This greatly reduces tooling costs, and makes the process suitable for medium to very large sized parts. However, the interaction between a flexible bag and the infusion of the laminate within, presents a significant challenge to model and understand. The University of Auckland LCM research group is developing SimLCM as a generic LCM mould filling simulation. SimLCM has recently been extended to simulate RI, focusing on resin flow and laminate thickness predictions throughout the process. To accurately predict filling times, and the evolution of fluid pressure and laminate thickness during filling and post-filling phases, a detailed knowledge is required of the complex compaction response of the fibre reinforcement. While significant research has been published on modelling of the filling in RI, the post-filling period has received much less attention. This phase is, however, significant as spatial variations in laminate thickness are removed, preferably before the infused resin gels. Extending on previous work on rectilinear filling, this paper will present a program of RI experiments in a range of 2D flow geometries and the results will be compared to the predictions made using SimLCM. Special attention is given to the post-filling stage, and the validation of the new models developed for SimLCM. A selection of radial, peripheral and more complex filling situations have been addressed.

Monday, 16:30 – 16:50, room 3.402

SESSION [4A] Model development and verification of the Vacuum Infusion process for composite manufacturing

Galyna Goncharova, Mylène Deléglise, Sébastien Comas-Cardona and Christophe Binétruy

A new analytical formulation of governing equations for hydro-mechanical coupled problem during single sided molding processes such as Vacuum Infusion (VI) is presented in this study. The main complexities of VI modeling are the presence of pressure changes and thickness evolution during fabric preform impregnation. The research is focused on the relations between flow progression and pressure changes inside the cavity. The main purpose of the presented studies aims at improving the manufacturing process of composite parts using a proposed mathematical model of moving-boundary problem. The derivation of a mathematical model of the VI process is proposed. Formulas of resin flow front position and pressure distribution with respect to longitudinal coordinate and time are proposed. The closed form analytical solution results are validated with one-dimensional fluid flow experimental data for two types of boundary conditions: constant and variable with time inlet pressure. This paper presents the comparison between the proposed model, experimental data from the literature and Correia's et al. [1] model for flow front position and pressure evolution. The results of the proposed model show better prediction for flow front position and pressure profile evolution over time than Correia's et al. [1]. The proposed model in this paper gives new look inside the hydro-mechanical coupled problems of the single sided molding processes. An improvement of the mathematical prediction of the VI process has been achieved.

Monday, 16:50 – 17:10, room 3.402

SESSION [4A] **Numerical simulation of resin flow, mould deflection and reinforcement deformation in RTM Light processing**
Jamie G. Timms, Simon Bickerton and Piaras A. Kelly

A numerical simulation of the RTM Light manufacturing process must capture the interactions between resin flow, preform deformation and mould deflection that occur during filling and post-filling. From a numerical solution perspective, RTM Light is similar to the fluid-structure interaction (FSI) class of problems, where the 'fluid' is a saturating deformable porous media and the structure is a compliant mould. Previous implementations of RTM Light simulations have been based on a partitioned solution procedure, using independent solvers for the flow and structure modules and a fixed point iteration coupling method. While this type of coupling has been successfully implemented in the solution of a number of FSI problems, it is prone to instability when coupling between the subdomains is strong, as is the case in RTM Light. This paper presents the development of a finite element RTM light simulation and compares performance of a number of partitioned and monolithic solution approaches for solving the coupled structural and flow problem. The flexibility of the code is demonstrated by simulating the limiting cases of zero mould compliance (i.e. RTM) and complete compliance (i.e. Resin Infusion/VARTM), along with the intermediate case of RTM Light.

Monday, 17:10 – 17:30, room 3.402

SESSION [4B] **A multifunctional device for polymer/composite characterization**
Xavier Tardif, Yasir Nawab, Nicolas Boyard, Vincent Sobotka, Pascal Casari, Frédéric Jacquemin and Didier Delaunay

The control and optimization of heat transfers during the forming of composite 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 and the reinforcement, but also of the parameters describing the phase change kinetics and associated shrinkage. The experimental determination of these parameters induces the use of many instruments, which is time consuming. To address this issue, a home-built instrumented mould, dedicated to thermoset and thermoplastic composites, was designed to measure and/or identify several properties from a single experiment. This "PvT-α" apparatus allows the moulding of circular samples of 40mm diameter and 6mm thick while controlling the applied pressure on the sample and the temperature cycle on its surfaces. This mould is designed such as heat transfer is 1D within the thickness of the sample. Variation of volume as well as heat transfer between the sample and the mould are recorded. Then 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 amorphous and glassy states can be estimated as function of temperature. Parameters of crystallization kinetic model are also identified for thermoplastics. The evolution of the shrinkage as a function of the phase change is determined. Finally, the impact of the fibre content on all these parameters is investigated. Our methodology is illustrated from results on a semi-crystalline thermoplastic and a thermosetting material.

Monday, 16:10 – 16:30, room 3.403

SESSION [4B] **Using optical fibre-based sensors to characterize resin flow and mechanical properties in LCM processes**

Marc Waris, Pierre-Jacques Liotier and Sylvain Drapier

This contribution aims at setting up physical solutions to track resin flow and conversion in LCM processes. We have demonstrated previously that thermocouples, along with optical fiber sensor (OFS), can be successfully employed to track resin flow front (Peng et al., J. Comp. Mat. 2010 and 2011). Also, in the case of simple plate geometries, distributed optical methods have proved to be efficient to assess the impregnation scenario of resin infusion (Peng et al., Composites/A 2010). Since then OFS such as Fiber Bragg Grating (FBG) and etched optical fiber sensor were developed and adapted to RTM processing. More precisely, OFS were embedded inside the preform, with an accurate placement in order to reduce the intrusiveness of the sensor. Moreover an efficient sealing with the mold cavity was achieved thanks to feedthrough systems. Specific cases were designed in order to study common issues faced by composites manufacturers, such as realizing thick composites parts or coping with "ply-drops" during the filling stage. OFS have shown great potential to monitor physical parameters such as temperature, degree of cure, and strain inside the part during the process. Responses provided by the sensors were compared to numerical simulation with the aim of having a better understanding of the phenomena occurring during the process. Finally a smart tooling concept was tested with OFS integrated inside composite tools. This concept has demonstrated some potential in monitoring RTM process without any perturbations of the sensors inside the part. This concept will be extended to two industrial applications.

Monday, 16:30 – 16:50, room 3.403

SESSION [4B] **Cross-sectional monitoring of resin impregnation using an area-sensor array in an RTM process**

Ryosuke Matsuzaki, Seiji Kobayashi, Akira Todoroki and Yoshihiro Mizutani

It is difficult to visualize the flow in the cross-section direction, and most conventional methods for monitoring resin flow are limited to the in-plane direction. This study investigates the monitoring of the cross-section of resin impregnation using an area-sensor array during a resin transfer molding (RTM) process. The area-sensor array is mounted on a thin polyimide film that is integrated with the inter-digital electrode array and associated wiring, and forms the bottom layer of the stacked composite laminates. Each area-sensor is square-shaped and measures the capacitance and electrical resistance of the sensor region. First, we constructed the equivalent electrical circuit model of in-plane and out-of-plane impregnation. The validity of the model was confirmed by comparison with the experimental results.

Monday, 16:50 – 17:10, room 3.403

SESSION [4B] **Innovative approach to track flow-front in LCM-processes through pressure sensors for in-line quality control**
Claudio Di Fratta, Florian Klunker and Paolo Ermanni

Quality of laminates made by Liquid Composite Molding (LCM) processes is closely related to resin system impregnation. Problems like void or dry spot formation often result in flaws and defects, which are usually recognized only after the final part is manufactured, through standard conformity verification. In this work, an innovative approach to track flow-front progression has been developed, which can allow early quality control during impregnation stage. The system relies on using a minimum number of pressure sensors, strategically located in the cavity, which alone give enough information for flow-front estimation over the time. This estimation is done by comparing pressure values from sensors with the pressure distributions obtained by flow simulations in an optimization loop. A big effort has been done to set up a numerical code that in a fast way follows fluid progression along its flow paths. Tests show that, with this approach, the introduction of just three sensors provides a sufficient resolution of flow-front position.

Monday, 17:10 – 17:30, room 3.403

[PLENARY 2] **Advances in Out-of-Autoclave Prepreg Research: From the Laboratory to Large Scale Applications**
Pascal Hubert

The majority of high performance composite structures are manufactured in autoclaves. This well established process requires high infrastructure investment for autoclaves as well as high recurring tooling costs. The maximum component size is limited by the size of available autoclaves. Alternative processing methods need to be investigated in order to reduce production costs and broaden the supply base of composite structures. This presentation addresses the application of a relatively new class of composite materials using out-of-autoclave (OOA) technologies. The advantages of OOA processes include substantially lower infrastructure, tooling, and overall manufacturing costs. However, current OOA processes give poorer component quality and material properties, which has limited their application. The presentation outlines past and recent works on the characterization of OOA prepregs. The physics of air evacuation, void nucleation, resin infiltration and pressure evolution is presented, and how all this depends on prepreg material architecture, bagging conditions, location of vacuum ports, temperature and vacuum application, size, lay-up, and shape of the component.

Tuesday, 8:40 – 9:20, room 1.439

SESSION [5] **VARTM processing of glass fabric reinforcements coated with graphite nanoplatelets**
Rehan Umer, Eric Waggy and Alfred C. Loos

The processing characteristics of glass fabric reinforcements coated with graphite nanoparticles were investigated. Exfoliated graphite nanoplatelets (xGnP) were mixed in a solvent. Controlled amounts of xGnP solution were coated on to either one surface only or both surfaces of plain weave glass fabric and the solvent evaporated. Experiments were conducted to measure compaction response and permeabilities of the xGnP coated fabrics. It was found that xGnP coated glass reinforcements were stiffer than the pure glass reinforcements which reduced the final fiber volume fraction that could be obtained during VARTM processing. The in-plane permeability measurement results show that the xGnP coated reinforcements filled faster compared with the pure glass samples. This was mainly attributed to high porosity due to greater resistance to compaction during infusion. The transverse permeability of the xGnP coated glass fabrics did not show much change compared with the uncoated glass. xGnP coated glass fabric preforms were infused using SC-15 epoxy resin by the VARTM process and cured. Micrographs show that xGnP was uniformly dispersed in the glass fabric with negligible washout.

Tuesday, 9:20 – 9:40, room 1.439

SESSION [5] **Comparison between the numerical simulation program PAM-RTM and RTM-measurements on a flat plate**
M. Arnold, G. Rieber, M. Wahl and P. Mitschang

In this study, the calculated flow fronts of the Resin Transfer Molding (RTM) simulation program PAM-RTM are compared to RTM experiments. Using experimental data (2D-permeability measurements of a wide variety of reinforcement material) recorded by IVW's permeability measurement cell 2D-Capa-Perm. Oil is used as the flow medium as its viscosity is well known as a function of temperature. During the experiments, radial flow of the oil is detected by eight linear capacitive sensors making it possible to visualize the flow front position of every sensor with respect to time. The experiments are simulated with the program PAM-RTM which enables the user to record the flow front position with respect to time at every node in the finite element mesh. The flow front positions of the associated experiments were afterwards compared with those of the simulation. The comparisons are performed for three glass fiber fabrics (plain, twill 2/2 and satin1/7) utilizing different injection pressures and fiber volume contents. Results of the comparisons show, that the correlations between experiments and simulations match very well. However, with increasing anisotropic flow behavior the correlation between the simulated flow front and the sensor signals in experiment at 45 degree orientation to the K1 and K2 directions becomes worse.

Tuesday, 9:40 – 10:00, room 1.439

SESSION [5] Reactive flow of thermosetting resins: implications to LCM processing

Jesús Maldonado, Bryan Louis, Florian Klunker and Paolo Ermanni

The flow in textiles can be described by Darcy's Law, which states a relationship of fluid flux and pressure gradient, depending on the viscosity of the fluid and the permeability of the medium. For liquid composite molding processes, the viscosity and the permeability are usually assumed to be independent, only related to fluid (viscosity) and textile (permeability). This paper shows that for reactive flows, i.e. when the thermoset matrix is significantly curing during the injection, the permeability depends on cure progression and injection velocity. This is due to the laminar nature of the flow which is often present in LCM processes: Assuming the flow channels to be capillary tubes, the laminar streamlines at the wall are much slower, and therefore have a longer residence time within the tube than the central streamlines. This leads to a build-up of gelled resin at the walls, decreasing the diameter of the pore, and therefore the representative permeability. This behavior is simulated within capillary tubes and verified by experiments. The accuracy of the predictions can be improved, but the effect is evident and should be considered in the forthcoming simulations of highly reactive flows.

Tuesday, 10:00 – 10:20, room 1.439

SESSION [5] Characterisation of an inorganic based resin for the liquid moulding processing of composites for intermediate temperature applications

Pascal Beneditti, Gilles Dusserre, Thierry Cutard and Julitte Huez

The weight decrease of the aeronautical structures has been made possible in the past decades by the development of composite materials. Significant progresses have been achieved for various parts of the aircraft primary structure by replacing most of aluminium alloys by composites. A next step requires the development of new materials with functional properties, without impacting the mechanical properties. In particular a significant lightening would be possible if composite materials are able to work at intermediate temperatures. This aim is mainly related to the existence of matrix materials bearing temperatures up to 400°C. The properties of an inorganic matrix precursor are investigated in order to assess the compatibility of this polysilazane resin with LCM (Liquid Composite Moulding) processes. At the liquid state, the resin is characterized by rheometry. The thermomechanical behavior of the matrix (issued from this resin) is characterized by Dynamic Mechanical Thermal Analysis (DTMA) on composite samples and SEM (Scanning Electron Microscopy) observations of post-mortem samples help to point out the main difficulty to process the resin.

Tuesday, 10:20 – 10:40, room 1.439

SESSION [6A] **Value correction in the determination of transverse permeability values by using flow simulation in deformable porous media**
F. Klunker, M. Danzi, T. Lämmlein, B. Louis and P. Ermanni

The determination of through thickness permeability is usually performed by a "black box" principle: An inflow is generated by applying pressure boundary conditions or volume rate boundary conditions, e.g. with a 1D-flow; with Darcy's Law the permeability is evaluated, assuming a constant fiber volume fraction in the cavity. It is well known that in the through thickness direction textiles can be compacted. Due to the flow, the pressure loss in the fluid induces stress on the fibers, so that they are deformed. This has a strong implication in the determination of through thickness permeability, as the fiber volume content is not homogeneous. In this paper, numerical simulation is applied to predict the deformation behavior in the textile as a result of the fluid pressure. Based on the results of the simulation a procedure to measure the through thickness permeability in saturated state, which takes the change of fiber volume content into account, is presented and discussed. The conclusions concerning the method to determine the saturated through thickness permeabilities are: (1) permeability measurements in through thickness direction cannot be reliable without the knowledge of the compaction behavior, (2) it is not possible to measure the through thickness permeability at a single fiber volume fraction if the fiber volume fraction is low with respect to the relations of pressure gradient and compaction behavior.

Tuesday, 11:00 – 11:20, room 3.402

SESSION [6A] **Influence of textile parameters on the through-the-thickness permeability of woven textiles**
P. Mitschang, M. Glawe, D. Kreutz, G. Rieber and D. Becker

The impregnation of the textile with matrix is characterized by the permeability. Knowledge about the permeability allows the design of a fast and reliable process by permitting the prediction of the flow directions, velocities, and pressures. There is no consistent information available about the influence of textile parameters on permeability. In this study, 19 woven glass fibre textiles are selected to determine the effect of the weave, linear density, yarn density and filament diameter on the through-the-thickness permeability. The finish of all textiles has been left constant. The measurements have been conducted on an unsaturated z-permeability measurement device consisting of a small central injection port and an ultrasound sender and receiver that track the flow front height. The overall injected fluid mass is measured by a scale. There is a linear dependency of the time of flight of the ultrasound signal and the height of the flow front in z-direction. It was observed that a higher number of textile layers leads to lower permeability values at the same fibre volume fraction. A systematic pattern was developed to characterize textiles as dense and open weave textiles by the linear density and yarn density. The more open a textile is the higher is the influence of the fibre volume content on the through-the-thickness permeability. Further influences of the weaving have been observed. The results of this study allow the selection and tailoring of woven textiles with specific, permeabilities for different applications.

Tuesday, 11:20 – 11:40, room 3.402

SESSION [6A] **Optimization of 3D wetting permeability measurements**
Andrew George, Anthony Pickett, Justas Sirtautas and Klaus Drechsler

The simplest method for through-thickness permeability characterization is by point-infusion into the top of a stack of material. Nedanov and Advani presented a solution for the flow geometry at the point the resin reaches the bottom of the mold in point-infusion. The three unknown fabric permeability components can be difficult to solve, however. A ratio simplification method is proposed to greatly simplify the calculation of the permeability components. The effects of binders, the compressibility under a vacuum bag, and capillary pressure are also discussed. The robustness of this test method is evaluated in light of measurements from a selection of different fabrics

Tuesday, 11:40 – 12:00, room 3.402

SESSION [6A] **Analytic method to estimate multiple permeability components from a single rectilinear experiment in Liquid Molding Processes**
J. Lugo, S.G. Advani and P. Simacek

One of the important issues in Liquid Composite Molding modeling and simulation is the evaluation of permeability of individual system components such as flow enhancement media (distribution media) and multiple preform layups. Extensive work has been devoted to various methods of this evaluation. Majority of the work has focused on characterization of single type of fabric characterization. The experiment if conducted in radial set up can characterize permeability usually in the in-plane directions, under different compaction loads and evaluate its statistical variation. There is, however, a need for a simple experimental setup to provide distribution media permeability along with the permeability of fabric underneath it in the in-plane and through the thickness direction from a single experiment, albeit lower accuracy. In addition to providing an input to the model, it is an easy way to check new batch of materials, since the flow related properties are rarely checked by the manufacturer. Also, for realistic manufacturing, the permeability values depend on the combined effect of individual components. The number and orientation of preform plies may also influence the permeability values. Bag and peel ply materials, and even the de-bulking process, may interfere with flow enhancement media and this may require one to measure an effective permeability for combination of these materials. This paper will present a new approach for determining in plane permeability of the preform , the distribution media and the effective permeability of preform and the distribution in the flow direction and the transverse permeability in the through thickness direction from a single rectilinear experiment, which models the VARTM infusion. The approach is based on tracking the resin flow-front during linear infusion along the top and the bottom surface over a sample representing several material layups (a segment of which includes the flow enhancement media). Analytic solution of flow progression is used to derive estimates for permeability of all components/layups. The solution, the error due to the assumptions and approximations made and its limits of applicability are presented. Numerical techniques using flow simulation can be further utilized to improve the permeability estimate.

Tuesday, 12:00 – 12:20, room 3.402

SESSION [6A] In-plane permeability characterization of fiber metal laminates made by RTM process

Iñigo Ortiz de Mendibil, René Hoto, Juan A. García, Javier Andrés, Mariasun Sarrionandia and Jon Aurrekoetxea

Fiber metal laminates (FMLs) consist of alternate thin layers of metal and fiber-reinforced polymer-matrix composite. The FMLs are usually manufactured using autoclave processing. These processes are well established and offering excellent reliability and part quality but they are expensive to produce and dimensional restrictions apply. LCM processes seems to be a good candidate to replace the autoclave process. In order to carry out accurate numerical simulations, the permeability of the FMLs must be measured. In this research work the effective permeability of a FML stack has been measured as well as the permeability of the single porous phase.

Tuesday, 12:20 – 12:40, room 3.402

SESSION [6B] Developing a novel manufacturing technique for manufacturing natural fibre reinforced thermoplastics

S.M.R. Kazmi, R. Das, S. Bickerton, Q. Govignon and K. Jayaraman

Natural fibre reinforced thermoplastics have made their way into the manufacturing industry because of their light weight, acceptable mechanical properties and the sustainability. Injection and compression moulding methods have been used over the years to produce composites; however there is still room for improvement in terms of part shape, strength, cost, fire resistance and surface finish. This gives rise to the idea of developing a manufacturing technique that fulfils most of the requirements. This work aims to evaluate the achievable fibre volume fraction and consolidation homogeneity of natural fibre reinforced thermoplastics, manufactured under vacuum inside an oven. Unidirectional Flax ($310g/m^2$) and Polypropylene sheets were chosen because of their popularity in the manufacturing industry. Laminates were produced targeting the maximum achievable fibre volume fraction based on the compaction characterization of the three types. The sheets were heated inside an oven for an hour to the melting temperature of polypropylene, held for two hours and then left to cool to room temperature. Two variations in the manufacturing technique were explored. In the first case, the sheets were kept under vacuum throughout the process. In the second case, 50 mbar of vacuum was applied until the melting temperature of polypropylene was reached, and from then full vacuum was applied untill the laminate was cooled to room temperature. An apparatus was designed to record thickness, pressure and temperature of the laminates along with the temperature and pressure during the experiment. Thickness of manufactured laminates was measured physically to confirm the achieved fibre volume fraction. Cross-section of the laminates was examined under a optimal microscope to examine the quality of consolidation. Post experimental analysis was used to compare the methods and prove the feasibility of one of the methods for future development. This work will assist in developing a method to produce complex geometry natural fibre reinforced composites.

Tuesday, 11:00 – 11:20, room 3.403

SESSION [6B] Optimum processing conditions for the manufacture of bamboo fabric-polypropylene composites

Nurul Fazita Mohammad Rawi, Krishnan Jayaraman and Debes Bhattacharyya

Bamboo is one of the world's best known natural materials and one of the fastest growing plants. Bamboo fibres have attracted global attention as a potential alternative for synthetic fibres such as glass or carbon fibres because of their low-density and high specific stiffness and strength. Research on bamboo fibre-reinforced composites has generally been focused on the use of short fibres. However, long bamboo fibres possess many excellent properties when used as fabric such as high strength and modulus due to continuous fibres oriented on at least two axes. In this study, bamboo fabric was consolidated between polypropylene sheets by compression moulding under various processing conditions. Compression moulding was used as it is a suitable and easy way to consolidate polypropylene sheets with bamboo fabric. The effects of three compression moulding parameters; processing temperature, pressure and time, on the tensile, flexural and impact properties of the composite sheets were evaluated. The Taguchi method was adopted to determine the optimum set of the compression moulding parameters to achieve the maximum mechanical properties of the composites. It is observed that processing temperature significantly affects the mechanical performance of compression moulded bamboo fabric-polypropylene composites. A viscosity test was conducted and the results showed that higher processing temperature gives better flow of the polypropylene. High pressure and short processing time resulted in better mechanical properties of the bamboo fabric-polypropylene composites.

Tuesday, 11:20 – 11:40, room 3.403

SESSION [6B] The manufacture and mechanical properties of aligned long harakeke fibre reinforced epoxy composites

Tan Le and K.L. Pickering

Aligned long harakeke fibre reinforced epoxy composites were prepared using hand lay-up followed by compression moulding. Densities of harakeke fibre and epoxy resin were determined for the purpose of composite design. The evenness of composites fabricated by two different size moulds was compared. It was found that more even composites were produced when using a small mould than a big mould. In this work, the dependence of tensile and flexural properties of harakeke/epoxy composites on fibre content was also investigated. The results showed that the addition of fibre enhanced tensile properties of epoxy. The tensile strength and Young's modulus increased with the volume fraction of harakeke fibre. The flexural strength and flexural modulus increased as the fibre volume fraction increased up to 0.4. Further addition of fibre did not result in an improvement of composite flexural properties.

Tuesday, 11:40 – 12:00, room 3.403

SESSION [6B] **Effects of enzymatic fibre treatment on kenaf fibre reinforced recycled polypropylene composites**
M.R. Islam, M.D.H. Beg and A. Gupta

In this work, environmentally friendly enzymatic pre-treatment of fibre to improve the interfacial bonding and adhesion between fibre and matrix were carried out for kenaf fibre reinforced recycled polypropylene (RPP) composites. Composites were produced using twin screw extruder followed by injection moulding. Maleic anhydride grafted polypropylene (MAPP) was used as coupling agent in the blend. Fibre tensile property, density and morphological changes due to treatment were compared with untreated fibre and effects of those properties on composites properties were analyzed. Composites were characterized by various mechanical tests such as tensile and flexural testing. It was found that, TS of composites increased by 40% due to enzyme treatment of fibre. Processability of composites was studied by measuring melt flow index (MFI). It was found that by increasing the fibre volume, increased shear stress and torque during extrusion and moulding, as a result 40% fibre was found to be optimum loading. Thermal stability was analyzed through thermogravimetric analysis (TGA). Activation energy was calculated from TGA analysis using Broido's equation. It was found that enzymatic treatment increased the activation energies of the composites at the second stage of degradation. To understand any morphological changes due to treatment and reactive processing of the materials, scanning electron microscope (SEM) were examined. Environmental stability of composites was studied by measuring water absorption for different time intervals.

Tuesday, 12:00 – 12:20, room 3.403

SESSION [6B] **An experimental estimation of liquid absorption coefficient for cellulose nano-fiber films**
A. Javadi, K.M. Pillai and R. Sabo

While making polymer composites from natural fibers using the liquid composites molding (LCM) process, the fibrous porous medium inside the LCM mold undergoes swelling and porosity reduction as a result of enlargement of natural fibers due to liquid absorption. The preforms made from plant-derived cellulose nanofibers (CNF) have a potential for creating higher-quality and bio-based green composites. The absorption coefficient, b, plays a very important role in the modified continuity equation that is proposed for such swelling media for conducting LCM mold-filling simulations. Past research has shown that an ad-hoc value of unity for b is quite good for modeling flows in LCM molds packed with natural fibers. In this paper, a simple dipping experiment is proposed to estimate b directly using a microbalance. The final results indicate that b is indeed one for CNF preforms as measured with water as the wetting liquid.

Tuesday, 12:20 – 12:40, room 3.403

[SESSION 7] Technology Transfer: from Research to Industrial Applications
Peter Mitschang

After a short presentation of the main research focus of the Institut für Verbundwerkstoffe GmbH (Institute for Composite Materials) the funding possibilities for Small and Medium Enterprises (SME) in Germany and in the European Union will be introduced. Successful co-operations between research and industry and examples from sports, mechanical engineering, and material suppliers will be presented. These types of co-operations offer the enterprises an easy access to new technologies from which novel innovative products can be developed. Also advantages arise for the research institutes in the area of the public perception, the development of new research and technology fields, and last but not least adjusted to the needs of the industry training of the engineers.

Wednesday, 9:00 – 9:35, room 1.439

[SESSION 7] Technology transfer in Canada: closing the gap between Science and Volume Production
Edu Ruiz

University research and higher education plays a very significant role in the development and growth of regional economy. In the last decades, efforts have been centered in the technology transfer from university towards industry for speeding up the implantation of novel technologies. Different approaches have been used around the globe for closing the gap between fundamental research and applied development. This work presents the approaches used in Canada for technology transfer to large, medium and small-sized industry. Examples will be unveiled on the use of scientific knowledge to solve practical issues in aeronautics and house appliances industries.

Wednesday, 9:35 – 10:10, room 1.439

[SESSION 7] **Projects to programmes — Matching technology transfer approaches to company needs and resources**
Mark Battley and Graeme Finch

The size of a company, their needs and their available resources can have a significant influence on the best approach to undertaking industry focused research. Mark will present case studies of different approaches used at the Centre for Advanced Composite Materials, and discuss the relative effectiveness of each for ensuring effective industrial uptake of the research results.

Wednesday, 10:10 – 10:45, room 1.439

[SESSION 8] **Nanofibres in high performance composites: commercialisation of a platform technology**
Albert McGhee

Revolution Fibres is a successful high-tech start-up on the field of nanofibres with its own unique industrial-scale manufacturing, functional materials and an increasing number successfully commercialised products. Products incorporating their technology are being exported to major international markets including Australia and the USA. Revolution Fibres views nanofibres as a platform technology where nanofibres can be produced to meet the exact needs of the application, including metal, carbon, polymer and composite nanofibres are possible. They will discuss their transition from an R&D company to a commercialisation and collaborative hub translating their expertise across a range of application industries. The latest innovation to come from their product development pipeline is the use of continuous nanofibres for high performance composites — Xantulayr™. With independently verified performance improvements across a range of tests, Xantulayr™ is already making an impact in carbon fibre sporting goods.

Wednesday, 11:15 – 11:40, room 1.439

[SESSION 8] **Tooling for Racing Yachts**
Susan Lake

Large scale technology and extreme precision are now integral to both composites tooling and high performance racing yacht construction. Core Builders Composites is ORACLE TEAM USA's official boatbuilding facility for the 34th America's Cup and is currently building the AC72 catamarans that will defend the America's Cup in San Francisco in September 2013. The focus of this presentation is on the development and production of autoclave tooling particularly for short lead times one off projects as well as semi-production. The influence of materials on the tooling will be discussed as well as scheduling and cost considerations.

Wednesday, 11:40 – 12:05, room 1.439

[SESSION 8] **BMW i Project: Industrialisation of the RTM Process**
Simon Bickerton

The i project represents BMW's current drive towards sustainable and visionary concepts for mobility. This large project will result in the release of an innovative electric vehicle, and an exciting hybrid vehicle, in 2013 and 2014. Lightweight construction is central to the i project, and carbon fibre reinforced plastics are being used to manufacture the entire "Life Module", the fully structural framework enclosing the passengers. Dr Bickerton is currently on secondment to BMW (Landshut, Germany), and will provide an overview of the composite structures employed, application of the RTM process, and an indication of the scale of the process chain required to produce the i project vehicles.

Wednesday, 12:05 – 12:30, room 1.439

SESSION [9] **Fast impregnation of complex shapes for the manufacturing of high performance composites and its associated tooling**

Clemens Dransfeld, Kunal Masania, Erich Kramer, Marcel Siegfried and Stefan Klauser

Today's application of composites structures in aeronautical industry is limited by the high manufacturing cost due to the labour intensive character of the current manufacturing processes as well as the long processing times. When considering the resin transfer process (RTM) the cycle time is limited by two distinct phases: the impregnation phase and the curing phase. The compression resin transfer moulding (CRTM) process is characterized by the fact that injection is done in a partially opened cavity, thus permitting a faster distribution of the resin offering large potential to shorten the impregnation phase. This work aimed at investigating the underlying principles of CRTM and to understand how this process can be applied to complex aeronautical composite profiles, such as frames and beams. Starting from a plate tool with dwell pressure moulding capabilities, the principle of CRTM was successfully transferred to two different geometries, a closed rectangular overbraided section with a compliant core mechanism (denominated FX-core), and open C-section based on automated tooling with drawer. It was demonstrated that a reduction of impregnation time of several order of magnitudes could be confirmed. As an additional benefit the interfacial properties of the composite could be increased with this fast processing route.

Wednesday, 14:00 – 14:20, room 1.439

SESSION [9] **Numerical and experimental study of the infusion process for large scale industrial parts**

Romain Agogué, Pierre Beauchêne, Jérémy Mazzolini and Julien Valette

This work is dedicated to the modeling of the infusion process with a comparison between experimental data and simulation results, including material characterization. Two infusion cases are considered. First, a one dimensional flow experiment and, secondly a large scale industrial part with a stiffener and a spherical shape. We will first present the characterization of the compaction behavior of our materials (woven and interlock carbon fibre preforms). Dry and wetted compactions are considered. This characterization is an input of the proposed model, the output is the predicted thickness evolution of the fabrics depending on the infusion conditions. This prediction is then compared to experimental measurement of the thickness of the preform with respect to the time by measuring the local displacement of the vacuum bag. A digital image correlation is used for the 3D measurements of the displacement of the vacuum bag. This approach highlights the strong coupling between infusion and compaction and its effects on the part health.

Wednesday, 14:20 – 14:40, room 1.439

SESSION [9] **Resin flow simulation based on advanced reinforcement geometry modelling from yarn-scale to component-scale**
Andreas Endruweit, Frank Gommer, Joel Hutchinson, Spiridon Koutsonas, Andrew C. Long, Peter Schubel, Xueliang Xiao and Xuesen Zeng

The architectures of textile reinforcements were characterised experimentally at different length scales. The obtained data allowed geometrical models to be generated, for which impregnating resin flow was simulated. Transverse yarn permeabilities for random filament arrangements, modelled based on typical nearest neighbour distributions, are log-normally distributed and significantly smaller than permeabilities for uniform yarns. Flow velocity fields indicate probabilities for intra-yarn dry spot formation. Detailed modelling of flow channel geometries in unit cells of fabrics with complex architectures allowed in-plane and through-thickness permeabilities to be obtained, which are in good quantitative agreement with experimental data. For non-uniform fabrics characterised by distributions of fibre angles, typical mould filling patterns were predicted. Global permeabilities were determined, which showed variability in the same order as typical experimental results. Analysis of gaps between the reinforcement and the surface of a moulding tool at bends in the component geometry indicated racetracking at the outer radius of the bend and lagging of the flow front at the inner radius, as observed experimentally. Realistic simulation of the impregnation of preforms with dynamically varying thickness in processes with flexible tooling was enabled by combination of flow and compression modelling.

Wednesday, 14:40 – 15:00, room 1.439

SESSION [9] **Online process monitoring systems — benchmark and test study**
Reinhold Meier, Swen Zaremba, Florian Springl, Klaus Drechsler, Fabrice Gaille and Christian Weimer

Despite the ambitions for increasing numbers of Carbon Fiber Reinforced Plastics (CFRP) parts no reductions in quality aspects can be accepted. Therefore new quality inspection methods have been taken into account. Online Process Monitoring (OPM) systems offer the opportunity to monitor process data, compare them with the ideal course of the process and draw conclusions about part quality. In this study three commercially available OPM systems - Dielectrical Analysis (DEA), Direct Current Resistivity measurements (DCR) and Ultrasonic Technology (US) - are discussed for use in series production. DEA measures the change in dielectrical properties of the resin, DCR is based on resistivity changes of the resin during processing and US analyses changes in ultrasonic speed of the matrix material. All systems monitor flow front arrival, in-mold viscosity and curing. Furthermore effects of aged resin and varying mixing ratios and detection of toughening thermoplastics are investigated. For ideal comparison of the different OPM systems an RTM tool was designed in which all three OPM sensors are installed at the same time thus the compared data are simultaneously gathered within the same experiment. Finally, the systems are evaluated with respect to the above-mentioned criteria in order to support the choice of a dedicated OPM system depending on the specific case of operation.

Wednesday, 15:00 – 15:20, room 1.439

SESSION [9] **In-mould gel-coating for RTM and RIFT**
John Summmerscales

Styrene vapours from unsaturated polyester resin may affect worker health and comfort, can produce an odour nuisance for neighbours and may incur environmental burdens. In composite component manufacture, the adoption of closed mould processes (e.g. liquid composite moulding techniques including RTM and RIFT) significantly reduces styrene emissions. Gel-coats are applied to component surfaces for cosmetic reasons and/or to enhance durability or surface function. However, the coating is normally applied to the open mould and allowed to progress to the gel state over time while styrene vapours are released to the atmosphere. A novel concept for the in-mould gel-coating (IMGC) of fibre-reinforced polymer composites has been patented. Initial RTM studies were conducted with UK TSB "Meeting the Challenge of the Zero Emission Enterprise" funding and reported at FPCM-10. A postgraduate project demonstrated that the concept was viable in resin infusion under flexible tooling (RIFT, SCRIMP™, VARTM) processes. The on-going development of IMGC is continuing in the Framework Programme 7 funded InGeCt research project (FP7_R4SME_286520_InGeCt).

Wednesday, 15:20 – 15:40, room 1.439

SESSION [10A] **Out-of-autoclave processing of ribbed parts: technical, economic and environmental assessment**
Rémy Teuscher, Robert. A. Witik, Amaël Cohades and Véronique Michaud

In this work, we compared autoclave and out-of-autoclave (OOA) processes in terms of cost, quality and environmental performance. The autoclave serves as the baseline process, and is compared with an OOA prepreg and infusion process to produce carbon fiber reinforced flat panels. The influence of pressure on part quality was assessed; cost and environmental performance were then compared for each production process. It was shown that although energy has a noteworthy contribution to environmental performance, its reduction plays a limited role in lowering part cost. The most significant contributor to both cost and environmental performance was carbon fiber production and conversion. A generic OOA prepreg ribbed part was then considered and an alternative method to improve rib quality in an OOA process was proposed.

Wednesday, 16:00 – 16:20, room 3.402

SESSION [10A] **Modelling the internal core pressure during cure of out-of-autoclave honeycomb panels**

James Kratz and Pascal Hubert

Honeycomb panels offer an extremely high stiffness-to-weight ratio, and their use in large structures can reduce labour and part count. Further cost savings can be achieved if good quality parts can be manufactured by vacuum bag only processing. Unfortunately, non-metallic cores readily absorb moisture from the atmosphere, which can be released as steam during elevated temperature processing. The internal core pressures become relevant when consolidating out-of-autoclave prepregs with vacuum bag pressure because of the reduced compaction pressure — a maximum of only 1 atmosphere is available — compared to 3 atmospheres usually used during autoclave processing of honeycomb panels. Therefore, during cure, the core pressure may increase to a level where gas flow through the skin is possible. To develop a better understanding of the possible internal core pressures encountered during cure, a model was developed to predict the pressure increase in honeycomb cells from absorbed moisture. A leak term was added to the model to account for gas flow through permeable plain weave skins during cure. The model was validated using an instrumented test fixture that measured the internal core pressure during cure with cores conditioned at increasing humidity levels.

Wednesday, 16:20 – 16:40, room 3.402

SESSION [10A] **The effect of out-time and cure cycle on the consolidation of out-of-autoclave prepregs**

Timotei Centea, James Kratz and Pascal Hubert

Out-of-autoclave prepregs are initially only partially impregnated, with dry areas that allow initially gas transport and are subsequently infiltrated. The following experimental study focuses on the effect of prepreg out-time and cure cycle on consolidation phenomena for two OOA prepregs with different fabric architectures. First, both prepreg and neat resin are aged under controlled conditions to three different out-times, and the resin viscosity and prepreg microstructure are investigated by parallel plate rheometry and x-ray microtomography, respectively. Then, laminates are manufactured using four cure cycles in an instrumented tool capable of tracking part thickness in-situ; the cycles consisting of two different ramp rates (0.57°C/min and 2.78°C/min) and dwell temperatures (93°C and 121°C). Finally, the laminates are analyzed to determine their fibre volume fraction and porosity. The results show that the resin viscosity increases with out-time but that the prepreg microstructure remains the same; that the rate of consolidation during processing differs with out-time; that out-time can significantly reduce the quality of manufacturing laminates by inducing micro-porosity within the tows; and that higher ramp rates and dwell temperatures may mitigate or even eliminate this problem.

Wednesday, 16:40 – 17:00, room 3.402

SESSION [10A] **Investigation of co-LCM process and the co-cured laminar interface of carbon fiber composites**

Xuqiang Ma, Yizhuo Gu, Min Li, Yanxia Li and Zuoguang Zhang

The carbon fiber/epoxy composite laminates were fabricated using co-LCM (co-cured liquid composite molding) process with prepreg stack. The compaction of the laminates and the diffusion of the epoxy resin in preperg and the epoxy resin for co-LCM were investigated. Mode-I delamination fracture toughness G_{1c} and short beam shear strength were measured to evaluate the co-cured laminar interface property of the composite laminates, and the data were compared with those manufactured solely by prepreg molding and LCM (liquid composite molding), respectively. Moreover, the effects of the fiber orientation at the co-cured laminar interface between prepreg part and LCM part on G_{1c} were studied. The results show that the laminates processed by co-LCM have high compaction degree in the intralaminar plies and no resin-rich area can be found between the plies. It demonstrates that interdiffusion of the two kinds of resins takes place at the co-cured laminar interface. The interlaminar fracture toughness of the co-cured laminates has the average of the data in comparison with the cases for the prepreg and the LCM laminates, and this result should be ascribed to the resin interdiffusion at the co-cured laminar interface. The fiber orientation between the prepreg and the LCM parts, at the co-cured laminar interface, has significant influences on the G_{1c} results, and [45/90] is better to resist the interlaminar fracture, as well to resist the propagation of the delamination.

Wednesday, 17:00 – 17:20, room 3.402

SESSION [10B] **Injection of a complex preform by RTM: Optimisation of a mould design and process parameters**

R. Agogue, P. Ouagne, D. Soulat, C.H. Park, J. Breard and D. Zanelli

This work concerns the manufacturing of a composite tube using RTM process. During the preforming stage, a woven braid is laid down and stacked on a mandrel so that reinforcement plies form conical shapes with a defined angle. An innovative experimental preforming procedure has been developed to respect the specific angle. The resin injection step has been studied both experimentally and numerically. In this work a focus is applied on the optimization of the mould geometry and on the way the resin is injected within the preform to prevent the appearance of defects such as displacement of plies and porosity. Different optimization steps are described in this work and a mould geometry is proposed for this specific application and the quality of the part obtained is discussed and analysed.

Wednesday, 16:00 – 16:20, room 3.403

SESSION [10B] **Variability of fibrous materials: experimental and theoretical study**
F. Zhang, S. Comas-Cardona and C. Binetruy

Different types of fibrous reinforcement used for structural composites are available, e.g. woven, non-woven or non-crimp fabrics. The architectures of woven and non-crimp fabrics exhibit a quasi-periodic repetition of basic unit cell. As a result, local mechanical and transport properties can be represented by the effective properties of a typical unit cell. In the case of non-woven or random fibrous reinforcement, the statistical properties, such as the distribution of pore sizes and shapes, the degree of correlation and the interconnectivity of pores, govern the transport process and the macroscopic material properties. Therefore, accurate prediction of fibrous media properties depends on appropriate description and representation of the microstructure. As observed by experimental studies, for instance, the permeability is very sensitive to such variation and greatly affects composite manufacturing. The study is based on image analyses of a random mat fibrous architecture which is then used as input in the prediction algorithm for the effective permeability of a region of interest. By defining suitable sampling size in the fabric sample, a permeability field can be obtained from each sample and validated with the experimental radial injection results in terms of flow front geometry. The random field model of permeability is then constructed by statistical characterization techniques.

Wednesday, 16:20 – 16:40, room 3.403

SESSION [10B] **Multi-component LCM processing for aeronautical structural applications — the influence of deflection in metering and homogenization**
Florian Springl, Patrik Welz, Swen Zaremba, Christian Weimer and Klaus Drechsler

This paper summarizes important facts and their consequences for the introduction of a multi-component resin system for aeronautical LCM processes. A generic comparison of the cost impact of the change from one to multi-component resin system for LCM is given. Furthermore, this paper presents results regarding the influence of varying metering and mixing conditions of a thermo set resin on the quality of performance of the composite material. Finally a potential method for inline process monitoring of the homogeneity is presented.

Wednesday, 16:40 – 17:00, room 3.403

SESSION [11A] **Uncertainty quantification in Liquid Composite Moulding processes**

Bart Verleye, Dirk Nuyens, Andrew Walbran and Ming Gan

Variability of technical textiles plays an important role in Liquid Composite Moulding (LCM) processes and product quality. The numerical simulation of an LCM process depends strongly on the distribution of the volume fraction of the material. To obtain more realistic results, a distribution for the areal mass of the textile can be used as input, i.e., for every point of the mesh, an areal mass value is determined by a random field. The distribution used for the mathematical model has to be selected in agreement with the physical distribution. The random nature of the textile properties, make that different simulations have different results, although the simulations are created with the same macro parameters. This resembles the spread on experimental results and reveals the distribution of the output. To compute the average fill time or required tooling forces and their spreads, one can use the Monte Carlo (MC) method, being repeated random simulations, or the quasi-Monte Carlo (QMC) method, consisting of deterministic simulations of the random field. We show the QMC method to converge faster than the MC method and compare the obtained results with the results from a numerical simulation of the same LCM process without the usage of the random field to possibly differ a lot for certain outputs. One such output is the maximum fibre stress which is severely underestimated by the standard method.

Thursday, 9:30 – 9:50, room 3.402

SESSION [11A] **Neural network versus Kriging, surrogate models for LCM process optimization**

Abhishek Gupta, Piaras Kelly, Matthias Ehrgott and Simon Bickerton

In Liquid Composite Moulding (LCM) processes an optimal combination of a variety of manufacturing design variables must be chosen in order to minimize cycle time while keeping equipment, layout and running costs low. Such black-box function optimization can be achieved by integrating the process simulation algorithm with a meta-heuristic, such as a genetic algorithm (GA). However, the large number of function evaluations required by a GA combined with the computational expense of the simulations often makes this approach unaffordable. This issue is further emphasized when the filling and curing phases are coupled and an iterative optimization strategy becomes necessary. The use of a surrogate model, as a substitute to the expensive simulation algorithm, is a common technique for reducing the run-time of an optimization algorithm. Choosing such a model that suitably duplicates all the features and trends of the objective functions over the design space, is an important task. In this paper we compare two popular surrogate models, namely the artificial neural network (specifically the Cascade-Correlation Learning Architecture Neural Network) and kriging, and discuss their performance in terms of prediction accuracy and the run-time of the resultant optimization algorithm.

Thursday, 9:50 – 10:10, room 3.402

SESSION [11A] **Numerical study on consolidation process of T-stiffened skin in autoclave**

Yanxia Li, Min Li, Yizhuo Gu and Zuoguang Zhang

Numerical models were developed to study the consolidation process of anisotropic T-stiffened skin in autoclave cocuring process. Resin pressure and resin flow were analyzed. The predicted results showed that the resin flow in the plane direction was obvious and the total quantity of resin flow out in the corner was larger than in the web and flange. At the same time, the experimental data validated the predicted resin flow during the consolidation process of T-stiffener skin in autoclave process. The results of this study will be attributed to promote the manufacturing quality of the integral molding technology and ultimately lead to optimized skin/stiffener designs.

Thursday, 10:10 – 10:30, room 3.402

SESSION [11A] **Modeling the constitutive response of an anisotropic dual-scale flow**

Mohammad Rouhi, Maciej Wysocki and Ragnar Larsson

Today's trend in composites manufacturing is to reduce cost by, among other things, cutting down the number of operations required to produce a component. For example all the steps of impregnating the reinforcement, consolidation, forming and finally curing may be, in some cases, combined into a single processing operation. This leads to increasingly complex manufacturing processes with many interacting sub-processes occurring simultaneously on different spatial and temporal scales. In this context we are developing a unified finite-strain continuum framework [1-4], which we recently adopted towards modeling of dual-scale flows in composite manufacturing [5]. In this context, in the present work we consider the manufacturing of the so called Engineering Vacuum Channel (EVaC) prepreg materials as discussed in e.g. [6]. Even though our numerical framework is capable of modeling all the interacting sub-processes at ones, the constitutive models for these are still rare and have not been generalised in a proper continuum context. In summary, the idea of the present work is to emanate from the existing model for fluid flow in a rectangular channel (the so called Poiseuille flow) and generalise it in the finite-strain continuum context. The major task is then to extend our framework to account for anisotropic Darcian interaction on the macro scale and implement the constitutive model into it, while the minor task is to examine the interaction between preform deformation on different scales and the process of micro infiltration and macro flow. The major task is accomplished by introducing the anisotropic permeability model to our coupled displacement-pressure, non-linear finite element model, while the minor task is approached using a representative numerical example, displaying the relevant interactions between the involved sub-processes. The algorithm is then tested for drained conditions, and results are compared to the one in [5] for isotropic flow.

Thursday, 10:30 – 10:50, room 3.402

SESSION [11A] **Monolithic versus decoupled approach to couple Stokes/Darcy flows in extreme regimes for LCM process modelling**

L. Abou Orm, R. Troian, J. Bruchon, N. Moulin, P.-J. Liotier and S. Drapier

The present contribution is devoted to developing robust finite element solutions for coupling flows in both purely fluid region, ruled by Stokes equations, and fibrous preform region governed by a Darcy's law. Particularly the cases of low permeability of preform, down to 1E-15 m2, are of interest to model LCM processes. Both a decoupled approach, as proposed by Celle et al.[1], and a monolithic approach, as proposed by Pacquaut et al. [2] are investigated in severe regimes. Flows are solved using mixed finite elements, stabilized respectively with a bubble function (P1+/P1 mini-elements) and a sub-grid scale stabilization technique (ASGS) [3]. A special attention is paid to the interface conditions, namely normal stress and velocity continuity and tangential velocity constraint similar to a Beaver-Joseph-Saffman's condition. First, in the cases of flows normal and tangential to the Stokes-Darcy interface convergence rates are investigated, and a comparison with available analytical solutions is carried out. Second, the Method of Manufactured Solution is used to assess the convergence rate along with the solution robustness. From this comparison, it is shown that provided a very special attention is paid to the coupling conditions, very precise results can be obtained. More precisely, the decoupled approach has been stabilized regarding the system conditioning, with appropriate penalty factors which depend now on the physics of the problem. This approach is under validation in an industrial framework. As for the monolithic approach, it is now perfectly robust due to the introduction of the ASGS sub-grid scale stabilization, and is being assembled with thermo-physico-chemistry of the resin.

Thursday, 10:50 – 11:10, room 3.402

SESSION [11B] **Pultrusion system for continuous fiber reinforced thermoplastic composite**

Anin Memon, Toshihiro Motochika, Daisuke Hatano, Asami Nakai and Akio Ohtani

In this study, the pultrusion system for continuous fiber reinforced thermoplastic composite was presented. The design concept of pultrusion systems were described in the term of materials design, structure design and processing design. The materials design were used hybridization of glass fiber with jute fiber reinforced PLA and carbon fiber with aramid fiber reinforced PA66. The braiding technique manufactured a hybrid yarn arrangement in tubular preforms. The braided preforms were pulled through a heated die where the consolidation flow took place due to reduced matrix viscosity and pressure. The pultrusion experiments were fabricated the tubular hybrid composite. Impregnation quality was evaluated by microscope observation of the pultruded cross-sections. The flexural mechanical properties of the beams were measured by 4-point bending test.

Thursday, 9:30 – 9:50, room 3.403

SESSION [11B] **Modelling of laser welding process on thermoplastic composites**

Benoit Cosson, Mylène Deléglise, Wolfgang Knapp, Philippe Castaing and Christophe Binétruy

Thermoplastics composites for structural applications are under growing development from the aerospace (carbon fibers with PEI, PPS or PEEK matrices mainly) to the automotive industry (glass and carbon fibers with PP, PA). The plastic deformation they can provide and the assembly facilities through welding techniques are well appreciated. Among the available welding technics, laser offers the possibility to assemble materials in a precise and localized manner and can be easily automated. However, due to the presence of continuous fibers at a high fiber volume fraction, propagation of the laser energy through the composite that present local variation of fiber volume fraction is not as straight forward as in an homogeneous material. Modelling of the laser welding of a PA/continuous glass fiber is considered here. The study takes into account the microstructure of the composite in order to evaluate changes in local energy absorption and divergence directly linked with the local fiber volume fraction value. Modelling of the welding process is developed from the representation of the moving laser beam. The beam propagation through the composite thickness is considered thanks to the ray tracing method. The local polymer rheology is defined through the resultant temperature profile obtained at the interface and taking into account the influence of the local fiber volume fraction. When applied to non continuous fibrous structure, local fluid flow induced during the welding process is greatly influenced by the influence of temperature on the viscosity coefficient, affecting the weld line quality and geometry. Variability of welding seam geometry and quality along with the composites structures variability is then shown.

Thursday, 9:50 – 10:10, room 3.403

SESSION [11B] **Influence of processing conditions on the permeability of microfibril-reinforced composites**

Sylvester Tan, Arcot A. Somashekar and Debes Bhattacharyya

In-situ microfibril-reinforced composites (MFCs) that consist of linear low density polyethylene (LLDPE) and polyethylene terephthalate (PET) were manufactured by industrial processing methods, such as compression moulding, extrusion blow moulding, slit-die extrusion with calendering, and injection moulding. The objective of this work was to investigate the effects of processing methods on oxygen permeability of the manufactured MFCs. A comparison of the processing methods showed that compression moulded MFC film displayed the greatest improvement in permeability (48%), when compared to neat LLDPE film. Calendered MFC films and injection moulded MFC containers showed slight improvements of 18% and 25% respectively, over plain LLDPE. Extrusion blow-moulded film produced mixed results due to the presence of voids in the LLDPE matrix. An investigation into the cooling conditions was performed on the compression moulding unit. Films cooled under no pressure provided a 20% improvement only, in comparison to the 48% improvement found in films cooled under pressure. The reduction in improvement observed in the other processing methods is most likely due to the rapid cooling or lack of applied pressure during the cooling process.

Thursday, 10:10 – 10:30, room 3.403

SESSION [11B] **Synthesis and characterization of multi-walled carbon nanotube reinforced Poly Ether Ether Ketone composite**
Nikhil Shaun Mepurathu, Gavin Lawes, Akila Deeghayu Kumarasiri and Susil K. Putatunda

The primary focus of this study was to investigate the synthesis of homogenous multi-walled carbon nanotube (MWCNT) reinforced Polyether-ether ketone (PEEK) using a novel melt processing technique. The secondary objective was to characterize the mechanical and physical properties of this MWCNT reinforced composite. Multi-walled carbon nanotube reinforced PEEK composites having different weight percentages such as 1%, 5% and 10% of MWCNT were synthesized using a novel melt-processing method. The microstructures of these samples were analyzed using a scanning electron microscope to confirm the uniform distribution of carbon nanotubes in the polymer matrix. The mechanical properties of these samples, including toughness and yield strength were determined using ASTM standards. The transport properties of these composites such as electrical and thermal conductivity and magnetic properties were measured as a function of carbon nanotube content and compared with those of pure PEEK. The test results show that there was a uniform, homogenous distribution of carbon nanotube in this polymer composite up to 5 wt. %. The mechanical, electrical and thermal properties increased with increasing carbon nanotube content up to 5 wt. %. Beyond this MWCNT fraction, there was no significant improvement in properties.

Thursday, 10:30 – 10:50, room 3.403

SESSION [11B] **Elastic properties of short fibres reinforced polymers in the vicinity of a weld line**
Gilles Dusserre

Short fibres reinforced thermoplastic polymers are currently processed by injection moulding. Net-shape complex parts are produced at a high rate and the fibres allow to reach interesting mechanical properties compared to non-reinforced polymers. The fibres orientation distribution in the part is the result of flow processes involved while filling the mould. The final material is then heterogeneous with anisotropic material properties. These heterogeneities are particularly important in the weld lines, resulting from the merging of two flow fronts. In non-reinforced polymers, it is possible to keep non-affected properties in these areas if the material is hot enough to weld properly when the fronts merge. However it is not the case in reinforced materials since the fibres orientation is very significantly different in the flow front as in the bulk material due to the lack of shear, resulting in a poor mechanical properties area. A characterisation of the elastic properties of the weld line is here proposed. Tensile tests performed on specimen with and without weld lines are performed showing a significant decrease of properties in the first case, and 3D-Digital Image Correlation method is used to identify the evolution of the mean elastic modulus as a function of the distance to the weld line. The results are analysed by comparing the experimental values to those given by the commercial software Moldflow®, based on the Mori-Tanaka micro-mechanical model and the Folgar-Tucker model, which evaluates the second-order orientation tensor proposed by Advani and Tucker.

Thursday, 10:50 – 11:10, room 3.403

SESSION [12A] **Flow and heat transfer inside an autoclave**
N.E. Jimmy Olsson, T. Staffan Lundström, L-G. Westerberg and Tonny Nyman

This work, that involves both experiments and numerical simulations, concerns autoclave molding. An autoclave is basically a pressure vessel, where the entrapped and often highly compressed gas is heated and circulated in order to heat the components that have been placed inside the vessel. In the autoclave process, the desirable state would be that an even and optimal temperature existed in the whole part that is manufactured. Unfortunately, this is not always the case. All in all we need to get a better understanding of the flow inside an autoclave and the convective heat transfer from the heated gas to the composite components. In this work we have therefore investigated the flow behavior by performing qualitative measurements with particle image velocimetry inside an autoclave. The concept is to dope the gas within the autoclave with smoke and illuminate the smoke with a thin sheet of laser light. Captured images of the moving smoke are then cross correlated to give velocity fields. We have also investigated the heat transfer to the tool by measuring the temperature at multiple locations during heating. The obtained velocity field is used to produce inlet condition for the simulations, performed with Computational Fluid Dynamics, which subsequently are compared with the experimentally obtained tool temperature. The simulation technique may then be used to optimize both the tools, and the actual location of the tools inside the autoclave in order to improve quality and reduce costs.

Thursday, 11:30 – 11:50, room 3.402

SESSION [12A] **Preparation and optimisation of modified DGEBA-based epoxy resin as a self-healing composite matrix**
E.H. Lim and K.L. Pickering

This paper presents an optimisation study of a modified epoxy resin, consisting of thermoplastic poly(bisphenol-A-co-epichlorohydrin) dissolved in diglycidyl ether of bisphenol A epoxy resin (DGEBA), and cured with nadic methyl anhydride and an accelerator. The purpose of the modification was to produce a polymer capable of self-repair. Thermoplastic beads as the main element of the healing system were stirred in heated epoxy resin for at least 24 hours until fully dissolved in the solution. The viscosity of the blends before cure with varying concentrations of thermoplastics in weight percentage was measured for use as one of the performance indices of the composite matrix. In conjunction with the concentration of thermoplastic, the highest healing efficiency without significant deterioration of matrix properties was also targeted in obtaining the optimum matrix. The polymer was found exhibiting highest mechanical properties when cured at 80°C for 4 hours and further post-cured at 130°C for 3 hours. It was also found that the modified epoxy resin not only facilitated the cured matrix to self-repair, but also improved the mechanical properties. Overall, therefore, it has been shown that addition of thermoplastic does not have to disadvantage matrix properties. Most importantly, test results also show a promising healing efficiency.

Thursday, 11:50 – 12:10, room 3.402

SESSION [12A] **Compaction response and air permeability characterisation of out-of-autoclave prepreg materials**

Christopher M.D. Hickey, Jamie. G. Timms and Simon Bickerton

Out-of-autoclave prepreg materials offer the ability to produce high quality laminates without the size and cost constraints of traditional autoclave prepreg manufacture. Because of the lower pressures involved, the complete removal of air from the laminate before cure is critical to ensuring a void-free laminate is produced, and maximum mechanical performance is achieved. The rate and direction of air removal from the laminate can vary widely between materials, so an accurate understanding of the air permeability of the prepreg, both in-plane and through thickness, is critical for optimal process design for laminates of varying size, thickness and material. This paper presents the development of an experimental method to measure the decoupled compaction response and in-plane air permeability of out-of-autoclave prepreg materials using a radial air flow technique. Decoupling the compaction response and permeability allows for the implementation of an air removal simulation, including the effects of spatially and time varying thickness and permeability. Initial experiments on unidirectional tape and plain weave cloth materials have shown the cloth exhibits higher porosity under 1 atmosphere of pressure, resulting in higher in-plane permeabilities over each material's achievable volume fraction range, by approximately three orders of magnitude, as compared to the unidirectional material.

Thursday, 12:10 – 12:30, room 3.402

SESSION [12B] **Fiber orientation observation of jute fiber filled injection moldings**

Yuqiu Yang, Putinun Uawongsuwan, Cuntao Wang, Masuo Murakami, Hiroyuki Hamada and Asami Nakai

Natural fiber composites are considered to be very promising materials for the future. However, the mechanical properties of natural fiber composites are still comparatively low and highly scattered. In the study, the hybrid fiber concept was introduced whereby Jute and glass fibers were simultaneously incorporated to enhance the mechanical properties of the composite. And long fiber pellet pultrusion technique was adopted to prepare glass/PP or Jute/PP pellets. Because it is a new method which is able to fabricate composite pellets with relative long length fibers for injection molding process, where, glass/jute yarns were continuously pulled and coated with PP resin. A non-linear correlation between the fiber contents and tensile strength in the hybrid composites could be observed whereby the optimum hybridization of GF 10 wt% and JF 20 wt%. In particularly, fiber orientation of both jute and glass fibers are analyzed based on the SEM and X-CT observation results. Additionally, the fiber alignment correction factors of all the injection molded composites were calculated from the experimental tensile modulus. It is found that the fiber orientation was improved and more of them were aligned to MD direction under the hybrid effect. It is interested that with the addition of glass fiber into jute system material, both glass fiber and jute fiber could get better orientation. Therefore high modulus can be obtained even put small jute fiber into glass fiber/PP material system, for the soft jute fiber have help the rigid glass fiber orientated to flowing direction.

Thursday, 11:30 – 11:50, room 3.403

SESSION [12B] **Optimization of the manufacturing of twill bamboo fabric reinforced polypropylene hybrid composites laminates**

Nurul Mahmud Zuhudi, Xiaowen Yuan and Krishnan Jayaraman

In recent years, natural fabric thermoplastic composites have received much attention especially bamboo due to its attractive capabilities for structural applications. It is crucial to study the processing of bamboo fabric materials in order to achieve quality and cost-effectiveness in fibre reinforced composites. Though bamboo fabric has been widely utilized for several years in composite applications due to its high strength and abundance, much work has been concentrated on short bamboo fibre and very little work on using bamboo fabric. The effectiveness of twill bamboo fabric is expected to give higher strength performance due to its structure but the processing needs to be optimised. Bamboo fabric composites were fabricated using compression moulding due to its simplicity, gives good surface finish and relatively low cost in terms of labour and production. Further, the impregnation of the polymer into the fabric is easier in this process. As the fabric weave structure contributes to the impregnation quality which leads to the overall performance, the processing parameters of consolidation i.e. pressure, time, and weight fraction of fabric were optimized using the Taguchi method. This optimization enhances the consolidation quality of the composite by improving the composite mechanical properties, three main tests were conducted i.e. tensile, flexural and impact test. It is observed that the processing parameter significantly affected the consolidation and quality of composite. Hybrid bamboo glass polypropylene composite sheets were also fabricated using the optimum processing parameters found out for the bamboo polypropylene composites and mechanical tests were performed on hybrid composites.

Thursday, 11:50 – 12:10, room 3.403

SESSION [12B] **Effect of ultrasonic treatment on the compatibility and mechanical properties of oil palm empty fruit bunch (EFB) fiber reinforced polylactic acid composites**

A.K.M.M. Alam, M.D.H. Beg, D.M.R. Prasad and R. M. Yunus

In this research, environmentally friendly composites were prepared by renewable materials such as oil palm empty fruit bunch (EFB) fiber and poly lactic acid (PLA). Fibers contents in the range 10–40 wt% were incorporated in PLA using extrusion followed by injection molding to prepare EFB/PLA composites. In order to improve the compatibility between EFB and PLA, EFB was treated by ultrasonic method in presence of alkali solution. The EFB fiber content was optimized on the basis of tensile strength (TS) and tensile modulus (TM) tests. The melt flow index (MFI) of treated fiber incorporated composites was found to be higher than that of the Raw EFB/PLA composite. A significant improvement of the TS, TM and impact strength (IS) values of the composites were observed after simultaneous ultrasonic and alkaline treated EFB fiber reinforced PLA composites. These composites showed more thermal stability as examined by thermogravimetric analysis. Distinct fracture surface morphologies such as fiber breaking, fiber pull out, fiber-matrix adhesion of the samples were clearly observed by the scanning electron microscopy.

Thursday, 12:10 – 12:30, room 3.403

List of Authors and Affiliations

Paper 1: **Biobased thermoset resins and flax fibre reinforcements processed by Vacuum Assisted Resin Transfer Moulding** (p19, Session 2B)

Jens Schuster[1], Quentin Govignon[2], Simon Bickerton[2]

[1]*Institut für Kunststofftechnik Westpfalz, University of Applied Sciences Kaiserslautern, 66953 Pirmasens, Germany*

[2]*Centre for Advanced Composite Materials, The University of Auckland, Auckland, 1142 Glenn Innes, New Zealand*

Paper 2: **Fast impregnation of complex shapes for the manufacturing of high performance composites and its associated tooling** (p40, Session 9)

Clemens Dransfeld[1], Kunal Masania[1], Erich Kramer[1], Marcel Siegfried[2], Stefan Klauser[3]

[1]*University of Applied Sciences and Arts Northwestern Switzerland FHNW, Institute of Polymer Engineering, Klosterzelgstrasse 2, 5210 Windisch, Switzerland*
[2]*formerly FHNW, now at Katholieke Universiteit Leuven, Belgium*
[3]*RUAG Schweiz AG, RUAG Technology, Seetalstrasse 175, 6032 Emmen, Switzerland*

Paper 3: **Numerical prediction of permeability of textiles for the International Benchmark Exercise** (p16, Session 1)

Xuesen Zeng, Andrew C. Long, Andreas Endruweit

Faculty of Engineering — Division of Materials, Mechanics & Structures, University of Nottingham, University Park, Nottingham, NG7 2RD, U.K.

Paper 4: **Modeling the constitutive response of an anisotropic dual-scale flow** (p47, Session 11A)

Mohammad Rouhi[1, 2], Maciej Wysocki[1,2], Ragnar Larsson[2]

[1]*Swerea Sicomp, P.O. Box 104, 431 22 Molndal, Sweden*
[2]*Division of Material and Computational Mechanics, Department of Applied Mechanics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

Paper 6: **Multi-component LCM processing for aeronautical structural applications — the influence of deflection in metering and homogenization** (p45, Session 10B)

Florian Springl[1], Patrik Welz[2], Swen Zaremba[1], Christian Weimer[2], Klaus Drechsler[1]

[1]*Technical University of Munich, Institute for Carbon Composites, Boltzmannstraße 15, 85748 Garching, Germany*
[2]*Eurocopter Deutschland GmbH, Production Technologies and Project, 81663 Ottobrunn, Germany*

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Reinhold Meier[1], Swen Zaremba[1], Florian Springl[1], Klaus Drechsler[1], Fabrice Gaille[2], Christian Weimer[2]

[1]*Institute for Carbon Composites, TU Munich, Boltzmannstraße 15, 85748 Garching, Germany*
[2]*Eurocopter Deutschland GmbH, Industriestraße 4, 86609 Donauwörth*

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Galyna Goncharova[1], Mylène Deléglise[1], Sébastien Comas-Cardona[1, 2], Christophe Binétruy[1, 2]

[1]*Department of Polymers and Composites Technology & Mechanical Engineering, Ecole des Mines de Douai, 941 rue Charles Bourseul, BP10838, 59508 Douai Cedex, France*
[2]*Research Institute in Civil Engineering and Mechanics (GeM), UMR CNRS 6183, Ecole Centrale de Nantes, 1 rue de la Noe, BP92101, 44321 Nantes Cedex 3, France*

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Andreas Endruweit, Frank Gommer, Joel Hutchinson, Spiridon Koutsonas, Andrew C. Long, Peter Schubel, Xueliang Xiao, Xuesen Zeng

Faculty of Engineering — Division of Materials, Mechanics & Structures, University of Nottingham, University Park, Nottingham, NG7 2RD, U.K.

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M. Arnold[1], G. Rieber[1], M. Wahl[2], P. Mitschang[1]

[1]*Institut für Verbundwerkstoffe, Erwin-Schrödinger-Str. Geb. 58, D-67663 Kaiserslautern, Germany*
[2]*Audi AG, Innovation und IT, Werkzeugbau, D-85045 Ingolstadt, Germany*

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Abhishek Gupta[1], Piaras Kelly[1], Matthias Ehrgott[2], Simon Bickerton[3]

[1]*Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*
[2]*Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*
[3]*Centre for Advanced Composite Materials, Department of Engineering Science, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand*

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Thomas Bayerl, Hristo Valchev, Erhard Natter, Peter Mitschang

Institut für Verbundwerkstoffe, Erwin-Schrödinger-Str.Geb. 58, 67663 Kaiserslautern, Germany

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Matthias Dickert, David C. Berg, Gerhard Ziegmann

TU Clausthal, Agricolastrasse 6, 38678 Clausthal-Zellerfeld, Germany

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F. Zhang[1], S. Comas-Cardona[1, 2], C. Binetruy[1, 2]

[1]*Ecole des Mines de Douai, Polymers and Composites Technology & Mechanical Engineering Department, 941 rue Charles Bourseul, 59508 Douai, France*
[2]*Ecole Centrale de Nantes, Research Institute in Civil Engineering and Mechanics (GeM) UMR CNRS 6183, 1 rue de la Noe, 44321 Nantes, France*

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E.H. Lim, K.L. Pickering

School of Engineering, Faculty of Science and Engineering, University of Waikato, Private Bag 3105, Hamilton, New Zealand

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Romain Agogué[1], Pierre Beauchêne[1], Jérémy Mazzolini[2], Julien Valette[2]

[1]*ONERA, , DMSC, 29 av. de la Division Leclerc, 92322 Châtillon, France*
[2]*Tensyl, 1, place Moitessier - BP 3123 - 17000 La Rochelle - France*

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S.P. Haanappel[1,2], B. Rietman[1], R. Akkerman[1,2]

[1]*Faculty of Engineering Technology, Chair of Production Technology, University of Twente, P.O. Box 217, 7500AE Enschede, the Netherlands*

[2]*ThermoPlastic composite Research Centre (TPRC), Palatijn 15, P.O. Box 770, 7500AT Enschede, the Netherlands*

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Benoit Cosson[1], Mylène Deléglise[1], Wolfgang Knapp[2], Philippe Castaing[3], Christophe Binétruy[1]

[1]*Ecole des Mines de Douai, Lille Eurorégion, 941 rue Charles Bourseul, BP410838, 59508 Douai cedex, France*

[2]*CLFA, Fraunhofer ILT, c/o Armines MINES ParisTech, 60 bld. Saint-Michel, 75272 PARIS cedex 6, FRANCE*

[3]*CETIM, 74, Route de la Jonelière - BP 82617, 44326 NANTES Cedex 03*

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Nikhil Shaun Mepurathu[1], Gavin Lawes[2], Akila Deeghayu Kumarasiri[2], Susil K. Putatunda[3]

[1]*Department of Mechanical Engineering, Wayne State University, Detroit, MI 48202, USA*

[2]*Department of Physics and Astronomy, Wayne State University, Detroit, MI 48201, USA*

[3]*Department of Chemical Engineering and Materials Science, Wayne State University, Detroit, MI 48202, USA*

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Claudio Di Fratta, Florian Klunker, Paolo Ermanni

Center of Structure Technologies, ETH Zürich, 27 Leonhardstrasse, 8092 Zurich, Switzerland

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Richard Loendersloot[1], Wouter Grouve[2], Edwin Lamers[3], Sebastiaan Wijskamp[4]

[1]*Applied Mechanics, University of Twente, P.O. Box 217, 7500AE, Enschede, The Netherlands*

[2]*Production Technology, University of Twente, P.O. Box 217, 7500AE, Enschede, The Netherlands*

[3]*Reden — Research Development Nederland, Twekkelerweg 263, 7553LZ, Hengelo, The Netherlands*

[4]*Ten Cate Advanced Composites, Campbellweg 30, 7443PV, Nijverdal, The Netherlands*

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Sébastien Guéroult, Laurent Bizet, Joël Bréard

LOMC, CNRS UMR 6294, Université du Havre, 53 rue de Prony, 76600, Le Havre, France

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A. Javadi[1], K.M. Pillai[1], R. Sabo[2]

[1]*Laboratory for Flow and Transport Studies in Porous Media, Dept. of Mechanical Engineering, University of Wisconsin-Milwaukee, 3200 N. Cramer St., Milwaukee, WI 53211, USA*

[2]*USDA, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 53726, USA*

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R. Masoodi[1], A. Javadi[2], K.M. Pillai[2]

[1]*School of Design and Engineering, Philadelphia University, 4201 Henry Ave, Philadelphia, PA 19144, USA*

[2]*Laboratory for Flow and Transport Studies in Porous Media, Department of Mechanical Engineering, University of Wisconsin-Milwaukee, 3200 North Cramer St., Milwaukee, WI53211, USA*

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Xavier Tardif[1], Yasir Nawab[1,2], Nicolas Boyard[1], Vincent Sobotka[1], Pascal Casari[2], Frédéric Jacquemin[2], Didier Delaunay[1]

[1]*Université de Nantes, CNRS, Laboratoire de Thermocinétique de Nantes, UMR 6607, La Chantrerie, rue Christian Pauc, BP 50609, 44306 Nantes cedex 3 — France*

[1]*Université de Nantes, Institut de Recherche en Génie Civil et Mécanique, UMR CNRS 6183, 37 boulevard de l'Université, BP406, 44600 Saint-Nazaire, France*

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A.K.M.M. Alam, M.D.H. Beg, D.M.R. Prasad, R. M. Yunus

Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, Gambang 26300, Kuantan, Malaysia

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M.R. Islam, M.D.H. Beg, A. Gupta

Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, 26300 Gambang, Kuantan, Malaysia

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Ridzuan Ramli[1], Rosli M. Yunus[2], Beg M.D.H.[2], Rohaya Mohamed Halim[1], Astimar A. Aziz[1], Ropandi Mamat[1], Zawawi Ibrahim[1]

[1]*Malaysian Palm Oil Board (MPOB), P.O. Box 50720 Kuala Lumpur*

[2]*Faculty of Chemical and Natural Resources Engineering, University of Malaysia Pahang, Gambang-26300, Kuantan, Pahang Darul Makmur, Malaysia*

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James Kratz, Pascal Hubert

McGill University, Department of Mechanical Engineering, 817 Sherbrooke St. West Montreal, Quebec H3A 3C0, Canada

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Rehan Umer[1], Eric Waggy[2], Alfred C. Loos[2]

[1]*Khalifa University of Science, Technology & Research, P.O. Box127788, Abu Dhabi, UAE*

[2]*Department of Mechanical Engineering and Composite Vehicle Research Center, Michigan State University, East Lansing, MI 48824-1226, USA*

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Tan Le, K.L. Pickering

School of Engineering, The University of Waikato, Hamilton, New Zealand

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Rémy Teuscher, Robert. A. Witik, Amaël Cohades, Véronique Michaud

Laboratoire de Technologie des Composites et Polymères (LTC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 12, CH 1015 Lausanne, Switzerland

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Andrew George[1], Anthony Pickett[2], Justas Sirtautas[2], Klaus Drechsler[2]

[1]*Swerea SICOMP AB, PO Box 271, SE-94126, Piteå, Sweden*
[2]*Institute of Aircraft Design, University of Stuttgart, Pfaffenwaldring 13, DE-75069 Stuttgart, Germany*

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Steven Phillips[1], Pei-Yu Kuo[2], Larry Lessard[1], Mohini Mohini Sain[2], Pascal Hubert[1]

[1]*Department of Mechanical Engineering, McGill University, 817 Sherbrooke Street West, Montreal, Canada, H3A 0C3*
[2]*Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, Canada, M5S 3B3*

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Timotei Centea, James Kratz, Pascal Hubert

Department of Mechanical Engineering, Faculty of Engineering, McGill University, MacDonald Engineering Building, 817 Sherbrooke St. West, Room 367, Montreal, Quebec, H3A 0C3, Canada

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R. Agogue[1, 2], P. Ouagne[1], D. Soulat[3], C.H. Park[4], J. Breard[4], D. Zanelli[5]

[1]*University of Orleans, Institut PRISME, France*
[2]*ONERA*
[3]*ENSAIT, Gemtex*
[4]*University of Le Havre, Laboratoire Ondes et Milieux Complexes (LOMC), France*
[5]*Roxel Company, Direction Technique et Industrialisation, France*

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Nurul Fazita Mohammad Rawi, Krishnan Jayaraman, Debes Bhattacharyya

Centre for Advanced Composite Materials (CACM), Department of Mechanical Engineering, The University of Auckland,Private Bag 92019, Auckland, New Zealand

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Nurul Mahmud Zuhudi, Xiaowen Yuan, Krishnan Jayaraman

Centre of Advanced Composite Material (CACM), Department of Mechanical Engineering, School of Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

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Gunnar Rieber[1], Jinhua Jiang[2], Carsten Deter[1], Nanliang Chen[2], Peter Mitschang[1]

[1]*Institut fuer Verbundwerkstoffe GmbH, Erwin-Schroedinger-Strasse, Geb. 58, 67663 Kaiserslautern, Germany*

[2]*College of Textiles, Donghua University, China Engineering Research Center of Technical Textiles, College Building 3, No.2999, North Renmin Road, Shanghai, China*

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P. Mitschang, M. Glawe, D. Kreutz, G. Rieber, D. Becker

Institut fuer Verbundwerkstoffe GmbH, Erwin-Schroedinger-Strasse, Geb. 58, 67663 Kaiserslautern, Germany

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Jesús Maldonado, Bryan Louis, Florian Klunker, Paolo Ermanni

Centre of Structure Technologies, Swiss Federal Institute of Technology Zurich, Leonhardstrasse 27, 8092, Zürich, Switzerland

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F. Klunker, M. Danzi, T. Lämmlein, B. Louis, P. Ermanni

Centre of Structure Technologies, ETH Zürich, Leonhardstrasse 27, 8092 Zurich, Switzerland

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Iñigo Ortiz de Mendibil[1], René Hoto[2], Juan A. García[2], Javier Andrés[3], Mariasun Sarrionandia[1], Jon Aurrekoetxea[1]

[1]*Department of Mechanics and Industrial Production, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragon, Spain*

[2]*Universitat Politécnica de Valencia. Camino de Vera s/n, 46022, Valencia, Spain*

[3]*Universidad Jaume I. Vicent Sos Baynat, s/n, 17071 Castellón, Spain*

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Yanneck Wielhorski, Amine Ben Abdelwahed, Laurent Bizet, Joël Bréard

Laboratoire Ondes et Milieux Complexes, LOMC, UMR 6294 CNRS, 53 rue de Prony, BP 540, 76058 Le Havre, France

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J.A. García[1], Ll. Gascón[1], E. Ruiz[2], F. Lebel[2], F. Trochu[2]

[1]*Universidad Politécnica de Valencia. Camino Vera s/n, 46022, Valencia, Spain*

[2]*Chair on High Performance Composites (CCHP), Département de Génie Mécanique, École Polytechnique de Montréal, Montréal, Canada, H3C 3A7*

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Jonas De Greef[1], Yichen Shen[2], Christoph Hahn[2], Stepan V. Lomov[3], Dirk Roose[1], Bart Verleye[1], Ignaas Verpoest[3]

[1]*KU Leuven, Dept. Computer Science, Celestijnenlaan 200A, B-3001 Leuven, Belgium*

[2]*TU München, Lehrstuhl für Carbon Composites, Boltzmanstr. 15 85748 Garching, Germany*

[3]*KU Leuven, Dept. of Metallurgy and Materials Engineering, Kasteelpark Arenberg 44 B-3001 Leuven, Belgium*

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Bart Verleye[1], Dirk Nuyens[1], Andrew Walbran[2, 3], Ming Gan[3]

[1]*Dept. Computer Science, KU Leuven, Celestijnenlaan 200A, B-3001 Leuven, Belgium*

[2]*Lehrstuhl für Carbon Composites, Technische Universität München, Boltzmannstraße 15, 85748 Garching bei München, Germany*

[3]*Centre for Advanced Composite Materials, University of Auckland, Private Bag 92019, Auckland, New Zealand*

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J. Lugo, S.G. Advani, P. Simacek

Department of Mechanical Engineering and Center for Composite Materials, University of Delaware, Newark, DE 19711, USA

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Florian Klunker[1], Widyanto Surjoseputro[2], Santiago Aranda[2], Daniel Beermann[2], Gerhard Ziegmann[2]

[1]*Centre of Structure Technologies, Swiss Federal Institute of Technology Zurich, Leonhardstrasse 27, CH-8092 Zurich, Switzerland*

[2]*Institute of Polymer Materials and Plastics Engineering, Clausthal University of Technology, Agricolastrasse 6, D-38678 Clausthal-Zellerfeld, Germany*

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Christoph Hahn[1], Christophe Binetruy[2], Roland Hinterhölzl[1], Klaus Drechsler[1]

[1]*Lehrstuhl für Carbon Composites, Technische Universität München (TUM), Boltzmannstraße 15, 85748 Garching, Germany*

[2]*Institut de Recherche en Génie Civil et Mécanique (GeM), Ecole Centrale de Nantes, 1 Rue de la Noë, 44321 Nantes, France*

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E. Ruiz, F. LeBel, F. Trochu

Chaire sur les Composites à Haute Performance (CCHP), École Polytechnique de Montréal, C.P. 6079, Station Centre-ville, Montréal (Québec), H3C 3A7, Canada

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Pascal Beneditti[1, 2], Gilles Dusserre[1], Thierry Cutard[1], Julitte Huez[3]

[1]*Université de Toulouse; Mines Albi, INSA, UPS, ISAE, ICA (Institut Clément ADER); Campus Jarlard, F-81013 Albi cedex 09, France*
[2]*Nexeya Systèmes 14 avenue Didier Daurat — Z.I. de Montaudran, 31400 Toulouse, France*
[3]*CIRIMAT-ENSIACET, bâtiment ENSIACET, 4 allée Emile Monso — BP44362, 31030 Toulouse cedex 4 — France*

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Gilles Dusserre

Université de Toulouse; Mines Albi, INSA, UPS, ISAE, ICA (Institut Clément ADER); Campus Jarlard, F-81013 Albi cedex 09, France

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John Summmerscales

Advanced Composites Manufacturing Centre, School of Marine Science and Engineering, Reynolds Building, Plymouth University, Plymouth, PL4 8AA, England

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Marc Waris, Pierre-Jacques Liotier, Sylvain Drapier

Département Mécanique et procédés d'élaboration, LCG UMR 5146, Ecole Nationale Supérieure des Mines de Saint-Étienne, Saint-Étienne, France

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Yi Hou[1, 2], Sebastien Comas-Cardona[3], Sylvain Drapier[2], Christophe Binetruy[3]

[1]*Polymers and Composites Technology & Mechanical Engineering Department, Ecole des Mines de Douai, 941 rue Charles Bourseul BP 10838, 59508 Douai, France*
[2]*Mechanics and Materials Processing Department, LCG UMR CNRS 5146, Ecole Nationale Superieure des Mines, 158 cours Fauriel, 42023 St Etienne cedex 2, France*
[3]*Research Institute in Civil Engineering and Mechanics (GeM), UMR CNRS 6183, Ecole Centrale de Nantes, 1 rue de la Noe, BP 92101, 44321 Nantes Cedex 3, France*

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L. Abou Orm[1], R. Troian[1, 2], J. Bruchon[1], N. Moulin[1, 2], P.-J. Liotier[1], S. Drapier[1]

[1]*Mechanics and Materials Science Division & LTDS UMR CNRS 5513, Ecole Nationale Superieure des Mines de Saint-Etienne, Saint-Etienne, France*
[2]*ARMINES, Paris, France*

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Xuqiang Ma, Yizhuo Gu, Min Li, Yanxia Li, Zuoguang Zhang

School of Materials Science and Engineering, Beihang University, Xueyuan Road, Haidian District, Beijing 100191, China

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Yanxia Li, Min Li, Yizhuo Gu, Zuoguang Zhang

Key Laboratory of Aerospace Materials and Performance (Ministry of Education), Beihang University, Beijing 100191, China

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Yuqiu Yang[1], Putinun Uawongsuwan[2], Cuntao Wang[2], Masuo Murakami[2], Hiroyuki Hamada[2], Asami Nakai[3]

[1]Donghua University, Shanghai, China

[2]Kyoto Institute of Technology, Kyoto, Japan

[3]Gifu University, Gifu, Japan

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Anin Memon[1], Toshihiro Motochika[1], Daisuke Hatano[1], Asami Nakai[2], Akio Ohtani[2]

[1]Department of Advanced Fibro-Science, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto, 606-8585, Japan

[2]Department of Mechanical Engineering, Gifu University, 1-1 Yanagido, Gifu, 501-1193, Japan

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Ryosuke Matsuzaki[1], Seiji Kobayashi[2], Akira Todoroki[2], Yoshihiro Mizutani[2]

[1]Tokyo University of Science, 2641 Yamazaki, Noda, Chiba, 278-8510 Japan

[2]Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro, Tokyo, 152-8552 Japan

Paper 91: **A 2.5D simulation of the filling and post-filling stages of the Resin Infusion process** (p26, Session 4A)

Quentin Govignon[1], Lucas Maes[2], Bart Verleye[1, 2, 3], Simon Bickerton[1], Piaras Kelly[3]

[1]Department of Mechanical Engineering, Centre for Advanced Composite Materials, The University of Auckland, New Zealand

[2]Department of Metallurgy and Materials Engineering, Composite Material Group, Katholieke Universiteit Leuven, Belgium

[3]Department of Engineering Science, Centre for Advanced Composite Materials, The University of Auckland, New Zealand

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Sung Ha Kim[1], Sung Woong Choi[1], Mei Xian Li[1], Chung Hae Park[2], Woo Il Lee[1]

[1]Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea

[2]Laboratoire d'Ondes et Milieux Complexes, UMR 6294 CNRS, University of Le Havre, Le Havre, France

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N.E. Jimmy Olsson[1], T. Staffan Lundström[1], L-G. Westerberg[1], Tonny Nyman[2]

[1]Division of Fluid and Experimental Mechanics, Luleå University of Technology, SE-941 87 Luleå, Sweden

[2]Saab Aeronautics, SE-582 54 Linköping, Sweden

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Gaston M. Francucci[1], Analia Vazquez[2], Edu Ruiz[3], Exequiel S. Rodriguez[1]

[1]*Composite Materials Group, Research Institute of Material Science and Technology (INTEMA-CONICET). Materials Engineering Department, Engineering Faculty, National University of Mar del Plata. J. B. Justo 4302, B7608FDQ, Mar del Plata, Argentina*

[2]*Polymer and Composite Material Group (INTECIN-CONICET) University of Buenos Aires. Las Heras 2214, CP 1127, Buenos Aires, Argentina*

[3]*Chaire sur Composites à Haute Performance (CCHP), Centre de recherches en plasturgie et composites (CREPEC), École Polytechnique de Montreal, C.P. 6079, Station Centre-Ville Montréal (Québec), H3C 3A7, Canada*

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Jamie G. Timms[1], Simon Bickerton[1], Piaras A. Kelly[2]

[1]*Centre for Advanced Composite Materials, Department of Mechanical Engineering, The University of Auckland, Auckland, New Zealand*

[2]*Department of Engineering Science, The University of Auckland, Auckland, New Zealand*

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Hai Long Liu, Wook Ryol Hwang

School of Mechanical Engineering, Research Center for Aircraft Parts Technology (ReCAPT), Gyeongsang National University, Gajwa-dong 900, Jinju, Korea, 660-701

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S.M.R. Kazmi, R. Das, S. Bickerton, Q. Govignon, K. Jayaraman

Department of Mechanical Engineering, Faculty of Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

Paper 102: **Influence of processing conditions on the permeability of microfibril-reinforced composites** (p49, Session 11B)

Sylvester Tan, Arcot A. Somashekar, Debes Bhattacharyya

Centre for Advanced Composite Materials, Department of Mechanical Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand

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Christopher M.D. Hickey, Jamie. G. Timms, Simon Bickerton

Centre for Advanced Composite Materials, Department of Mechanical Engineering, School of Engineering, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand