10th International Conference on Flow Processes in Composite Materials — Monday 12 July 2010
Centro Stefano Franscini, Monte Verità Ascona, Switzerland — AM 0800-1200

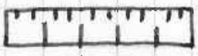
Welcome — Veronique Michaud, EPFL
~95 delegates from 11 countries - 2 student fellowships: Argentina & New Zealand

Centro Stefano Franscini — Regula Störrlein, CSF MV.
- "Hill of Truth" - vegetarian community and sanatorium
- now run by Ticino Foundation and ETH Zurich
- meeting platform for international scientific community since 1989

Simulation of RTM processing of a composite fan blade for an aircraft engine — Edu Ruiz, Ec. Poly. Montréal.
- SNECMA/GE joint venture CFAN International
- Leading Edge Aviation Propulsion (LEAP56™) 2.5m long × up to 40mm thick.
- 3D aerodynamic design as 3D damage tolerant Jacquard woven CF preform
- manufacturing issues: random cycle times, impregnation, short shots, undercure...
- characterisation of materials: rheological, thermal, chemical
- characterisation of the RTM process: cure, permeability, heat transfer, voids
  - ⇒ Kamal-Sourour cure kinetics, Dibenedetto glass transition
  - ⇒ resin viscosity modelled as a function of time, temperature and degree of cure
  - ⇒ permeability as a function of direction, draping/shearing
    - 80% reduction in K_1 at 30° shearing angle, and locally on mould curvatures.
  - ⇒ thermal conductivity as a function of volume fraction, direction and temperature
- >300 000 3D element FEA on 8CPU Win32 server - simulation time = 1 week
- validation as injection pressure vs time plot OK for $\mu = f(T,\alpha)$: weak for $\mu = f(CTE)$ or $\mu = f(\cdot)$.
- process optimisation
  - ⇒ capillary impregnation: Washburn's law and Young-Laplace equation
    - black light illumination of impregnation with pigmented resin
  - ⇒ constant flow front advance rate to minimise void formation (at blade tip)
- Future: 2014 CFM-LEAP-X1C turbofan for Chinese COMAC aircraft (2016).

Industrialisation, optimisation of RTM process applying mfg. process simulation — François Dumont, Eurocopter
- application is structural components of NH90 troop carrier helicopter.
- MPS (manufacturing process simulation) to complement CATIA design using PAM-RTM/CFX/CFD++.
- risks: (a) immature MPS, (b) pull-mode "fireman syndrome, (c) organisational mismatch

Manufacturing a composite gearbox for rotorcraft applications — Jeffrey Lawrence, V Systems
- housing of bevel gear where main shaft turns to drive tail rotor.
- replacement of three part magnesium alloy with 2-part composite
- 50% increase in loading whilst maintaining minimum safety factor of 6.
- simulations using LIMS 5 software ⇒ void-free first part (CATIA tools for pattern setting)

Effect of groove configurations on fatigue resistance of infused sandwich panels — Lars Massüger, 3A / Alcan Airex (→ now 3A Composites)
- Airex GP grooves 2.5mm deep, 1.5mm wide at 20mm spacing
- ContourKore (blocks on scrim)
- Asymmetric double cut: 30mm spacing displaced on opposite face 
  - ⇒ ~~reduced~~ equivalent mechanical properties, but higher resin uptake and ∴ higher density for DC

Injection of a complex preform by RTM: process parameters and quality of part — Pierre Ouagne, Orleans

- component is a double-tapered tube: fibre orientation n/a for braiding
- low pressure start to injection to avoid preform buckling

Void formation during preform impregnation in LCM processes — Ranga Pitchumani, VirginiaTech
- plain weave modelled as lenticular cross section following a sinusoidal path
- Newtonian, incompressible laminar flow with continuity of flow, momentum & volume
- permeability of tow assumes aligned unidirectional cylinders (square or hexagonal packing)
- 35K elements/unit cell in ANSYS FLUENT (3 cells ∴ 105K total elements)
- slower resin flow has longer fill times but requires less resin to achieve minimal voids

Analysis of voids and saturation in the RTM process — Chung Hae Park, U Le Havre
- air entrapment dry spots due to race tracking
- inter-bundle channel flow (macropore) — monophase analysis: incompressible fluid (IF)
- intra-bundle tow void (micropore) — multiphase analysis: IF + compressible air

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On wetting of a fibre with a resin by capillary force — Yoshizumi Fukuhara, UTokyo
- 20 μm glass fibre 550 mPa.s epoxy resin
- imaging of movement of fluorescent particles

3D mesoscale mapping of the fluid content in partially impregnated reinforcement textiles using high-resolution magnetic resonance imaging — Andreas Endruweit, UNottingham
- Perspex/nylon 140 × 90 × 4.7 mm cavity mould
- vacuum driven injection of engine oil into 0/90 NCF E-glass or short random CF preform
- image of 500 μm cube? 500 μm voxel? CHECK paper for correct values?
- scan times 7 minutes (FLASH) to 21 minutes (for useable resolution)!
- 45 mm transition zone with warp fibres only wetted.
- apparent variation in signal intensity corresponding to weft/inter tow spacing?
- dry spot detected and imaged at 109 pixels than 78 pixels.

ROUND TABLE on Industrial Applications — PM 1500-1900
Bodo Fiedler (Chair – Ruag Aviation), Hans Henry, Jeffrey Lawrence, Mathias Wietgrefe, Clemens Dransfeld
Porsche looking for 50% materials cost reduction and 90% production cost reduction
Key issue is mould-close to mould-open time ~ looking for cure-off-the-tool

A study on the effect of Joule heating during LCM and cure of CFRP. — Nikolaos Athanasopoulos, UPatras
Using CF reinforcement as heating element ρ_f = 9-18 μm m

In-mould gel-coating for RTM & RIFT — JS, ACMC Plymouth

Observations from the filling and post-filling stages of axisymmetric LCM with flexible tooling — Jamie Timms, UAuckland
RTM Light monitored with stereophotogrammetry cameras

Comparing flow front propagation: fibre Bragg gratings vs LIMESS Vic3D — Jordy Dalvers, TU Delft
LIMESS Vic3D = three dimensional contactless full field measurement

Vacuum infusion processing of composites with integrated damping elements — Antoine Sigg, EPF Lausanne
NiTi SMA wires for SMECMA European DREAM project
Dow DER 332 resin / IM7 or 5-harness satin with FBG strain gauge

X-ray microtomography and pull-out test to characterise fibre-fibre contacts in short fibre reinforced composites during their processing — Pierre Dumont, UGrenoble
glass fibres in paraffin wax. x-ray synchrotron source. seeking # bundle-bundle contacts / bundle

TUESDAY 13 JULY 2010

Prediction, measurement and significance of reinforcement permeability — Andrew Long, UNottingham
preform variability: ply placement, nesting, differential compression, fibre/tow waviness
experimental accuracy: viscosity, racetracking, mould deflection, measurement error, data handling

A reference porous medium made by rapid prototyping as a calibration tool — Krishna Pillai, UWisconsin Milwaukee
Accura 60 stereolithographic photopolymer resin

Evaluation of resin impregnation process in textile fabrics — Asami Nakai, Kyoto IT
3D hollow Raschel knitted fabric in glass fibre

An optically based inverse problem to measure in-plane permeability fields — Simon Bickerton, UAuckland
Digital SLR photography fibre on light box to identify tow/gap spacing
Image processing to identify centre of gravity of crossing # and join dots for orientation/waviness
Create porosity map and solve for permeability map.

Experimental and numerical analysis of the deformation of woven composite reinforcement - consequences on the permeability. — Emmanuelle Vidal-Sallé, INSA Lyon
High resolution x-ray microtomography
Compression transverse to plane of fabric
Shearing of fabric - non uniformity of void space shape in CT images.
Void shape and tortuosity dependent on nesting

Validation of flexible permeability characterisation methods in numerical simulation. Enrique Diaz, AIMPLAS
Cost effective vacuum infusion for large parts e.g. GAMESA & OCQUETEAU
Experimental fill of complex component +10% time re simulation

Correlation of permeability values with flow channel diameters determined by 3D image analysis of a woven textile — Gunnar Rieber, U Kaiserslautern
390 gsm twill weave glass fibre with differing ends/m (670) & picks/m (600)
x-ray micro CT with fibres subtracted to identify (resin) flow paths.
- pore spaces then filled with fictitious balls (spheres) ⇒ granulometry
- cumulative distribution of increasing sphere diameter vs fibre volume fraction
- Hazen formula $K = C_H D_{10}^2$ where D_{10} : particle size for 10% is finer, C_H = Hazen constant
- Hagen-Poiseuille capillary tube model $K = d^2/32$ (1D) or $K = d^2/96$ (3D)
- calculating global isotropic permeabilities but need different quantiles/V_f

Comparison and evaluation of two different permeability measurements — Mathias Wietgrefe, DLR
carbon bias non-crimp fabric 12K HTS 268 gsm from Saertex as $[0/90°]_{2s}$ laminate V_f = 54-68%
fluid = Cannon S2000 viscosity standard fluid for rheometer calibration 66.25 mPas @ 100°C
1D constant pressure 4 bar max pressure @ EPFL - some racetracking?
2D constant volume flow 12 bar max pressure @ DLR
EPFL values slightly higher than DLR permeabilities, but sensibly of same order.

INTERNATIONAL PERMEABILITY BENCHMARK — Bertrand Laine, ONERA; Nuno Correia
G1112 2x2 twill glass AND G986 2x2 twill carbon
1D and 2D flow in-plane (plus through-thickness) - saturated and unsaturated flow
http://cchp.meca.polymtl.ca/permeabilityBenchmark11.html to participate

Permeability prediction for a REV of a fibrous media with a monolithic FEM — Grégory Puaux, CNRS
Level set function and Stokes flow equations
Gebart or Tamayol lubrication model, Happel cell model, Bruschke & Advani hybrid model

Permeability of woven fabrics: analytical and numerical predictions — Bertrand Laine, ONERA
Comparison of Hivet/Badel vs WiseTex THEN Abaqus/WiseTex THEN Avizo/IDEAS THEN CELPER
Stokes between tows, Brinkman within tows in combination ⇒ Lattice Boltzmann, FEA, FD etc
Permeability prediction suggests nesting modifies permeability by factor >30 for UL and LL of domain
Influence of Brinkman contribution increases with V_f
Good agreement between Hivet/Badel and WiseTex below 40° shearing angle

Development of a multigrid finite difference solver for benchmark permeability — Richard Loendersloot, Twente
residual = difference - operator x estimate
many elements required for accurate solution but results in slow convergence rate.
multigrid uses coarse mesh for fast convergence to a rough solution then interpolate and return to coarse mesh cycle interpolation/restriction to obtain accurate solution
4-level MG converges in 1829 s, 3MG in 3419, single grid in 36745 s (latter not converged!)

A simplified computational treatment for non-isotropic permeability flow models. Nicolas Montes, CEU Cardenal-Herrera
From Cartesian Space to Configuration Space Concept (Flow Pattern Configuration Space: JCOMA 2010 41(1) 58
⇒ Flow Pattern Display Space ⇒ optimal channel distribution design (with secondary branches)
Flow Pattern Permeability Spaces (FPKS) for anisotropic flow fields using circle-ellipse transformation.

Alteration of permeability caused by transverse flow induced deformation — Vilnis Frishfelds, LuleåUT/ULatvia
Stream function: minimisation of dissipation rate of energy (Kim & Karilla 1991)
Discretisation using modified Voronoi diagrams.

Numerical simulation of coupled Stokes/Darcy flow applied to LCM at the mesoscopic scale (continuing from Grégory Puaux talk) — Luisa Silva, Mines Tech Paris
interface defined by zero isoset in Level set Function.
fine scales is a bubble function as a stabilisation matrix.

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Wednesday 14 June 2010
AM 0800 - 1200

Process development for complex RTM components: optimisation — Gion Barandun, ETHZ
- systematic process development using evolutionary algorithms as a minimisation problem
- quality = f (flow front velocity, length and angle at confluence zones) + fill grade% + fill time
- takes 14 hours on a 28 processor cluster for 2.5D using nose component.

Proper generalised decomposition of LCM models — Adrien Leygue, Nantes/EADS/Valencia
- complexify (move to high dimensionality problems) and evaluate for an a priori solution
- for X-D problems, moves to N^x degrees of freedom (curse of dimensionality)
- so move from mesh to separated representation d.o.f. = n × N × dimensionality
  - superposition of modes but beware unseparable parameters (esp. x-, y-, z- spatial dimensions)
- for LCM move from 3D to (2D + 1D) in PGD (proper generalised decomposition)
- [-45/+45] laminate: spiral flow path parallel to fibres until boundary reached then other orientation.
- ⇒ accurate and VERY FAST solutions of previously insoluble problems,
  - e.g. 5 minutes in MATLAB environment vs. 2 million DOF finite element model.

Numerical simulation of resin flow in fibre reinforcement with stochastic.. — Fan Zhang, EMDouai
- numerical solver for stochastic partial differential equations
  - ⇒ Ghanos + Spanem spectral stochastics finite element method.

Combining a level set method and a stabilised mixed formulation P1/P1 for coupling Stokes/Darcy flows: application to resin-infusion based processes — Sylvain Drapier, ENSM St Etienne
- unstructured mesh to avoid fluttering velocities at the Stokes - Darcy interface (pure fluid vs porous media)

Modelling the resin flow of reactive ~~liquids~~ resins in liquid composite moulding — Suresh Advani, CCM Delaware
- RTM - RTM Lite - VARTM - compression RTM using scripting rather than coding
- Distribution medium in VARTM modelled as 2D in plane due to difficulty of determining K_z.
- Viscosity solution now connected to temperature and degree-of-cure (and heat dispersion during flow)
- Convection and dispersion of cure need to be addressed
- LIMS sufficient for isothermal, but non-isothermal problems needs
  - three stage solution: temperature - infiltration - cure
  - Tucker - Dessenberger (diffusion/dispersion of cure) Kamal - Sourour (reaction) + Han-Lee (viscosity)

Development and verification of a model of a resin infusion process during manufacture of a fibre-metal laminate by VARTM — Al Loos, Michigan SU
- Titanium foils and "graphite" polyimide composite for FML
- Flow visualisation using glass reinforcement, plastic films, PC mould tool and oil as fluid
- Hexagonal hole spacing in acetates at 12.7 or 25.4 mm pitch, ∂ 0.41, 0.83 or 1.59 mm diameter
- Holes modelled as rectangular porous strips
- Modelled in FLUENT (blue = empty, green = partial fill, red = fully wetted)

A unified continuum mechanics approach to composites manufacturing modelling — Maciej Wysocki, SICOMP
- "compressible" two phase continuum ⇒ uniaxial compression for degree of saturation of TwinTex

Experimental observation and analytical modelling of resin flow in OOA prepreg — Timotei Centea, McGill U
- 5-harness satin in MTM45-1 epoxy semi preg from ACG. 60 minutes vac'd at ambient temp, ramp to 85°C
- 7 µm/pixel x-ray CT scan (4000×2096 pixel image) ⇒ 500+ microslices (25 GB data total)
- slow temperature ramp allows longer for extraction of air through dry tows

Simulation of non-isothermal prepreg press process for high volume automotive applications — Florian Klunker, TU Clausthal
- Energy balance equation modified to include changing heat capacity
  - high dependence on temperature <Tg, relatively insensitive >Tg.

Constitutive modelling of UD reinforced thermoplastic laminates — Sebastiaan Haanappel, U Twente
- Placement of tailored prepreg tape blanks for press/stamp forming in the molten state
- Deformations arising from intra-ply shear, inter-ply shear, tool-ply slip and out-of-plane bending
- Ideal Fibre-Reinforced Newtonian fluid medium (IFRM)
- Higher viscosity (300 kPa.s vs 4 kPa.s) results in lower wrinkling

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AM 0800-1230

Processing plant fibre composites with LCM: from comparisons to opportunities — Laurent Bizet, Le Havre
Partial review of the key considerations with comprehensive data graphs for mechanical properties
Permeability of flax preform down by factor-three relative to glass fibres?

Capillary effects in VARTM with natural fibres — Exequiel Rodríguez, U Mar del Plata
capillary pressure = -0.0025 MPa (i.e. one-quarter of injection pressure)
dependence of results on test fluid. Contact angle is not constant

An approach to model resin flow in LCM preforms made of swelling liquid-absorbing natural fibres — Krishna Pillai, U Wisconsin
Swelling reduces gross porosity of preform and hence reduces permeability
Damaged fibres (i.e. broken cell walls) swell more than intact cells
Swelling inversely proportional to the molecular weight of the swelling fluid
Saturated fibres behind flow front reduce effective porosity and hence reduce permeability behind flow front
significant increase in "diameter" of jute fibre after one-minute in water
- absorptions reported between 6-100% by weight for water (zero change for motor oil)

Processing and mechanical properties of UD hemp/paper/epoxy composites — Gilbert Lebrun, U Quebec-TR
high density paper up to 85% fibre volume fraction as carrier for UD hemp fibres
some waviness in the hemp consequent upon no tension in the natural fibres
UQTR propose very thin paper layer to hold UD fibres together
Carrier can be printed with graphics or have other functionality (i.e. functional paper products)
Higher modulus but lower strength for NF-only vs NF/paper composites, but brittle failure in latter
CoV of NF-only composites ~ 3 x CoV for NF/paper composite

Comparison in in-plane permeability between flax and glass-stitched fabrics — Christophe Re, U Le Havre
Confirms (or is it the same data) finding of Bizet that $K_{flax} \sim K_{glass}/3$.
[Stepan Lomov: stitch pattern dominates permeability relative to other factors]

Mechanical properties of short and continuous natural fibre/glass fibre hybrid composites — Yew-Wei Leong, Kyoto IT
- injection moulded short fibre composites with polypropylene matrix from dry blended pellets
- braided fibres in thermosetting VE resin with ±20° ±16° jute holding UD glass fibres/hybrid tows.
DG (degree of greenness) up to 20%

Compression moulding of flax fibre reinforced composite materials — Pierre Dumont, U Grenoble
Few experimental studies of natural fibre composite rheology: matrix = paraffin gel.
ESRF X-ray microtomography
- Low temperature and/or high strain rate ⇒ one phase flow
- high temperature and/or low strain rate ⇒ undesirable two-phase flow (component separation).

Study of the compaction behaviour of jute fabrics in LCM processes. — Gaston Francucci, U Mar del Plata
glass fabrics compress more easily than natural fibre reinforcements
significant increase in NF V_f on second cycle (fibre breakage & lumen collapse).
compaction pressure decreases as immersion time increases for NF.
(opposite occurs with glass fibres!)
Freundlich $\sigma(V_f) = a(V_f)^{bV_f}$ gives best fit to data.

microfibril
elementary cell/lumen 10-20 μm
technical fibre

Effect of processing on the durability of fibre reinforced plastics — Asami Nakai, Kyoto IT
Quasi-isotropic glass/epoxy by hand-lay, pre-wet or VARTM
Low cycle fatigue tests conducted at different stress levels (nonlinearity point from static test)!

Effect of water immersion ageing on impact resistance and flexural behaviour of hemp fibre reinforced unsaturated polyester composites — Hom Nath Dhakal, U Portsmouth
Low velocity instrumented falling weight impact test