Thirty Years of

COMPOSITES RESEARCH

@ Leuven

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LEUVEN | 2013

Written on the occasion of the 65th birthday of Prof. Ignaas Verpoest

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COMPOSITES RESEARCH

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PREFACE

Large scale structures are now part of our daily lives. We fly planes, build bridges and our houses are powered by wind turbines. As common as these structures may be, they are products of the ingenious work of engineers and materials scientists. Structures of such magnitude require materials that can support high loads and serve decades without failure. Moreover, they must perform in an efficient and environmentally friendly manner. In the language of engineers it implies that these materials must be light, stiff, strong and durable. The state of actual science today shows that fibre-reinforced polymer composites are champions in combining all that. This naturally brings forward the subject of this book – composites research at KU Leuven and people who have contributed to it over the course of more than 30 years.

Composites Research @ Leuven is written on the occasion of the 65th birthday of Prof. Ignaas Verpoest who started this line of research at KU Leuven in 1981 and has built a successful research group since then. Today the Composite Materials Group in the Department of Metallurgy and Materials Engineering is one of the largest university groups on composites in Europe. It is internationally known for its contributions to the fundamental and applied research on composites.

The book describes three decades of the research progress in the Group. Each decade carries a title that reflects the spirit of that period: "Learning the job" in the 80s, "Exploring the possibilities" in the 90s, "Getting focused" in the 2000s and "Going strong" for the current period. The book not only contains factual information about people, events and research results but also tells personal stories and provides insights into the world of composites. By writing this book, we wanted to better understand what motivated and inspired the Composite Materials Group all these years, which paths brought it to success and where it struggled. But most of all, we wanted to learn how it evolved into a group with the unique identity and strong sense of family it has today.

For the younger generation of researchers like myself, I believe, the book and its stories have something important to teach us about what it takes to build a successful research group and, more importantly, what it takes to make a real contribution. In fact, it is a lot more than to do excellent research, to build networks and to do service to society. One needs to have a great vision and passion for the field. Only then one person's career can touch and impact lives of so many.

I thank everybody who contributed to the book and Ignaas for giving me the opportunity to be part of this inspiring experience.

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ACKNOWLEDGEMENTS

Preparing a book like this takes time and energy, and requires the collaboration of many people. Several of them deserve to be especially acknowledged.

This book simply would not be in your hands if not for Ignaas Verpoest's idea to document the history of the Composite Materials Group. The first two chapters are mainly based on his memories, complemented by contributions of Jan Ivens.

Stepan Lomov, Larissa Gorbatikh, Jan Ivens, and Aart Van Vuure wrote major parts of the third and fourth chapters, focusing on research developments in the field of their expertise (textile composites, composites on the nano- and micro level, process and application development, and bio-composites, respectively). Together with Ignaas, they also co-wrote other chapters of the book.

Katleen Vallons, Joris Baets, Baris Sabuncuoglu, Sergey Ivanov, Ngoc Tran, Marcin Barburski, postdoctoral researchers in the Composite Materials Group, and Markus Kaufmann from SLC, helped to put together the fifth chapter of the book describing the Group's identity and vision for the future of composites.

Jo Mariën, Bart Pelgrims, Kris Van de Staey and Joris Baets provided indispensable input needed for writing the section about home-made equipment.

Sheron Shamuilia and the staff of the KU Leuven Research and Development office supplied the data and original graphics for the section on patents.

Current and former researchers of the Composite Materials Group are especially thanked for providing illustrations of their research work, photos and information about their theses. This book would not have been possible without their high quality research.

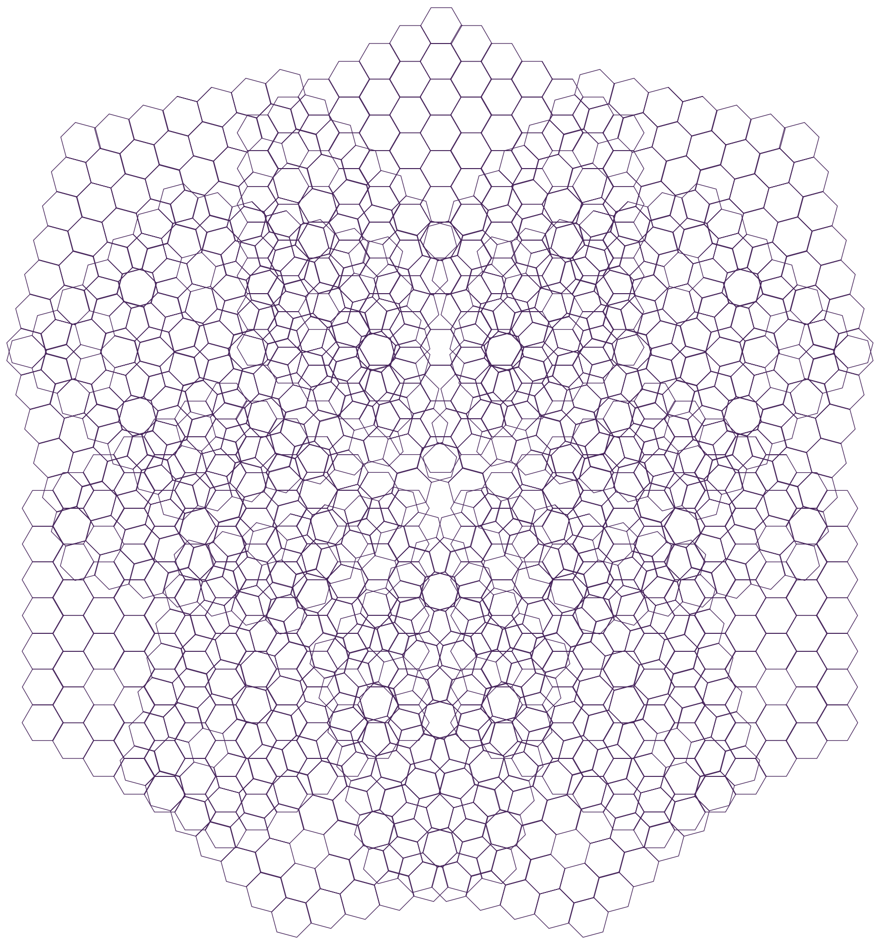
Kelly Vanden Bosche was very kind to read the entire book and correct everybody's language mistakes. She managed to do it under tight deadlines for which we are particularly thankful.

As the book was taking shape, we were extremely fortunate to have Hilde Princen (partner in *Van Looveren & Princen*) to come up with the beautiful design of the book and to patiently include all our wishes.

Anikó Lantos and Jennifer Hsiao were very helpful in providing general support, collecting information and arranging meetings.

The core team of Larissa Gorbatikh, Katleen Vallons and Ignaas Verpoest deserves special thanks as it worked tirelessly and sometimes sleeplessly to bring this book to you in set time. As editor, Larissa orchestrated the book preparation, kept an eye on all the moving parts in the project and motivated everybody.

Finally, we thank everybody who, in one way or another, contributed to the history of the Composite Materials Group in the last 30+ years: the colleagues and collaborators of the Department of Metallurgy and Materials Engineering, of the Faculty of Engineering and of the Materials Research Centre at KU Leuven, but also all those at other universities, research centers, government agencies and companies with whom the Group collaborated. Many of them have been mentioned in this book, but it was impossible to mention them all. We apologize if we have been incomplete!



CONTENTS

LEARNING THE JOB

1981-1989

In 1981, fifteen years after the worldwide market introduction of carbon fibres, the Department of Metallurgy at KU Leuven was still fully focused on metals. Wanting to be at the forefront of materials science, the department staff strongly supported the proposal to open a research line on composite materials.

The first part of this decade was devoted to 'learning the job'. The organization of composites workshops with Steve Tsai and George Springer played a big role. With the help of creative technicians, a composites lab could be realized with mainly home built processing equipment. Starting with only one PhD student, Martine Wevers, in 1981, the group expanded to five at the end of the decade, covering already four main subjects which would always be present from then on: damage development, fibre-matrix interfaces, textile based composites and application development.

1983 : The very first Composites Workshop at KU Leuven. On the front row, third and fourth from left, Steve Tsai and George Springer from Stanford University.

THE START

In 1981, Ignaas Verpoest defended his PhD thesis on "Fatigue of steel wires" guided by Prof. André Deruyttere and Prof. Etienne Aernoudt and in collaboration with the Belgian company Bekaert. During this research project, new experience was generated in fatigue testing and modeling of fatigue crack growth in metals. The very first fatigue testing machine in the department was built by converting a hydraulic tensile testing machine and later on, a second fatigue tester, a multiaxial Schenck (tension/torsion/ internal pressure), was installed.

The major technological challenge, namely measuring crack growth during fatigue testing in fine steel wires (<2 mm diameter), led to the development of a precise AC-potential drop method which was able to measure crack growth increments in the micrometer range. This advancement was the result of an intensive collaboration between the PhD-researcher and the lab engineers. Such intensive interaction would later on become one of the key characteristics of the Composite Materials Group in the Department of Metallurgy and Materials Engineering of KU Leuven (MTM-KU Leuven).

During the last year of this PhD-thesis, a request was received from the Belgian tennis racket manufacturers Donnay and Snauwaert to evaluate the dynamic mechanical and fatigue behavior of their newly developed composite tennis rackets. Composites, and certainly carbon fibre composites, were very new at that time. Both Donnay and Snauwaert, already world famous for their wooden tennis rackets, wanted to maintain their role as leaders in the market by using innovative materials. This exciting moment was the very first time composite materials were investigated at KU Leuven and foreshadowed a new era in research.

Even in those first days of composites research, a rich collaboration was being nurtured between various departments at KU Leuven and around Belgium. In working on composite tennis rackets, the Mechanical Engineering Department offered their experience in vibration and damping analysis, while MTM (together with the Free University of Brussels (VUB) and Ghent University) provided fatigue testing knowhow. A special device for alternating four point bending tests of tennis racket frame sections was constructed, allowing the innovative Donnay and Snauwaert composite tennis rackets to be optimized for fatigue resistance.

At about the same time that the tennis racket project started, the visionary leaders of MTM, impressed with the new field of composites, offered Ignaas Verpoest a position to stay as a post-doc researcher with the condition that a new field in materials research be opened. The research on composites, guided by Profs. Etienne Aernoudt, André Deruyttere, and Paul De Meester, coincided with the time that carbon fibre composites were finding their first applications, mainly in military aircraft and sporting goods. Even though composites were already entering the market, we had to start from scratch and build our own knowhow, because the composites industry was almost non-existent in Belgium except for some companies producing glass fibre composite parts.

The start of composites research in KU Leuven exemplifies what would now be called 'slow science': the department provided money and people to gradually build up the elementary experimental equipment and

Enjoying Belgian cookies after the first Composites Workshop: Steve Tsai, George Springer and Ignaas Verpoest, in front row Iris Tsai, Rita Delaet, secretary, Susan Springer and Martine Wevers, PhD student at that time

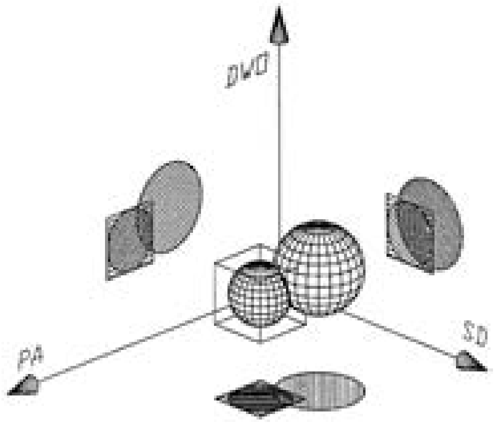
(Top) **Prof. Tsai with PhD-researchers including Jan Ivens and Philippe Rubbrecht**
(Bottom) **Prof. Springer with Ignaas Verpoest**

Ignaas Verpoest explaining to prof. André Deruyttere, head of the department at the start of the composites research at KU Leuven, the present he received at the occasion of Ignaas's 25 years at MTM (2001). Between them is visiting prof. Richard Parnas, to the right are Ignaas's daughter Lien and prof. Jan Ivens

knowledge necessary for making and testing composites. A small hot press was built by Jo Mariën and his technical staff, and an ultrasonic C-scan was built by engineering students of Groep T under the supervision of Joost Devos. Koen Mols, a PhD student continuing the research on metal fatigue, wrote the software for the C-scan. With these developments we were able to produce 20 x 15 cm plates with controlled temperature, pressure and vacuum, and have a quality control by means of ultrasonic C-scanning. In 1986, students worked on the construction of a drop-weight impactor, again under the supervision of Jo Mariën and Koen Mols for the software. In 1988, the first autoclave was realized as a re-engineered heat-exchanger vessel through a creative engineering effort of Jo Mariën, Joost Devos, Luc Peeters and Jan Ivens.

In the Summer of 1983, looking for an intensive course on composites to quickly catch up with the state-of-the-art in composites science and engineering, Ignaas Verpoest registered for a one week course on composites at the German Aerospace Centre (DLR, at that time called DFVLR) in Stuttgart. Lecturers Steve Tsai and George Springer trained students to apply laminate plate theory using hand-held Texas Instruments calculators with insertable magnetic strips: one strip for each step in the laminate analysis; a very didactical approach! He was so impressed, that he invited them to Leuven for a similar one-week workshop in 1984, which immediately attracted more then 30 participants from all over Europe, and was repeated in 1986, 1988 and 1990.

(Top) **1988: participants at the third Composites Workshop**
(Bottom) **1987: participants at the 'Effects of Defects' Workshop**



An early 'pattern recognition' approach to analyse acoustic emission signals *(from the thesis of Rony Van Daele)*

Martine Wevers and Ignaas Verpoest, receiving the 'Verbundwerkstoffmedaille 1984 in Gold' at the DGM-conference in 1984

The first master's theses in composites at MTM
In the academic year 1985-1986, Yves Bonte did the first "textile" master thesis on the 2.5D fabrics material, Dirk Borghs worked on damage during fatigue, as part of Martine Wevers' PhD. One year later, Jan Ivens started his research on interfaces and Gunther Van Bavel studied woven textile composites as part of the PhD thesis of Ronny Vandaele on PEEK-composites.

These workshops laid the foundation for a Europe-wide network of composites researchers and engineers from many universities and companies resulting in several collaborative projects. These workshops not only helped to put Leuven on the world map of composites research, but they were also the start of a life-long friendship with Steve Tsai and George Springer.

In 1989 an advanced "Level 2"-workshop was organized, which eventually would lead to the creation of the modular, one-year European master's degree program in Polymer and Composites Engineering in 1991 together with several partners from European universities, with whom we had collaborated in the very first Belgian and European projects. A EU-funded COMETT-program on "High-Tech Education in Composite Materials" was submitted and granted, the last step to the start of the EUPOCO program (see next chapter).

In parallel with developing both our experimental infrastructure and a sound scientific understanding, the first research projects were launched. Until 1984, the tennis racket project was the only externally funded composite materials project, but the MTM department supported the start of this new research group by including it in larger university (GOA on interfaces) and government funded (IUAP on materials science) projects. The latter helped establish a formal collaboration with Université Catholique de Louvain (UCL, Prof. Legras) and VUB (Prof. De Wilde and Cardon) furthering our interactions with other institutions.

EFFECTS OF DEFECTS

The PhD research of Martine Wevers on the damage development in carbon-epoxy laminates was a logical extension of the earlier work on fatigue and was building upon the NDT-experience of Prof. De Meester. Martine developed a methodology for using acoustic emission data to analyse the occurring damage. Her very first results were immediately awarded the

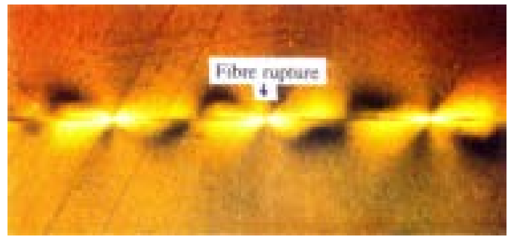
Damage history on the replicas taken after several fatigue cycles *(PhD thesis of Martine Wevers)*

"Verbundwerkstoffmedaille 1984 in Gold" of the Deutsche Gesellschaft für Metallkunde, 1984.

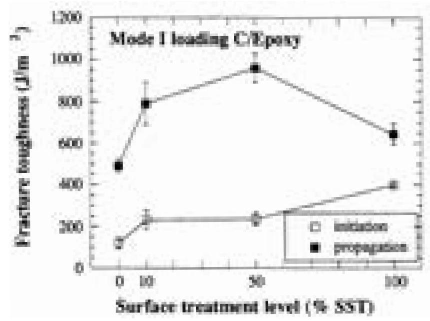
The second PhD student on composites, Rony Van Daele, developed an in-situ penetrant-enhanced radiography method that allows the measuring of damage development during incremental tensile testing.

Both of these PhD theses were linked to the first European project (1984-1987) in which the young composites research group at MTM-KU Leuven participated. This project, the EC-Twinning Program on "Damage development and failure processes in composite materials (Effects of Defects)" was in cooperation with the University of Surrey (Mike Bader, Antony Kelly), Université de Compiegne (Francois de Charentenay), DFVLR-Köln (Piet Peters, Karl Schulte) and RISO-Denmark (Hans Lilholt). The collaboration with most of these institutes continues to this day. In 1987, a symposium of the European twinning group on the "Effects of Defects" was organized in Leuven.

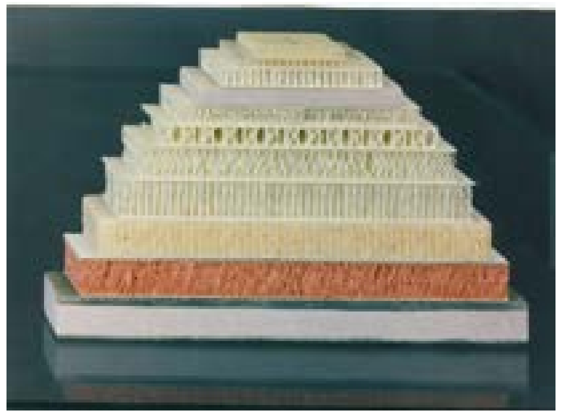
Jan Ivens performing in-situ X-ray measurements for damage detection during a tensile test



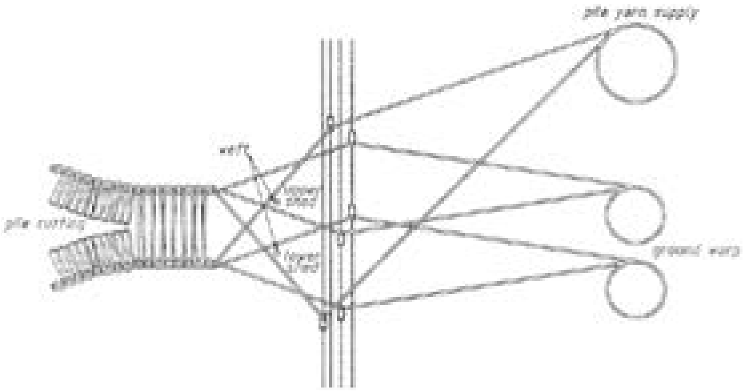
Strain field during a fragmentation test on a carbon fibre in epoxy matrix *(PhD Muriel of Desaeger)*



The effect of surface treatment on the interlaminar fracture toughness of carbon fibre epoxy composites *(PhD thesis of Jan Ivens)*



A pile of 3D-woven sandwich panels with different matrices (epoxy, phenolic, polyester)



Original scheme for making 2.5 D fabric

Prof. George Springer, receiving the MTM-medal from Prof. Etienne Aernoudt after one of his lectures during his sabbatical in KU Leuven in 1989

INTERFACES

The second European project was the Euram project on “Interfaces in Composites” (1988-1991), involving DFVLR Köln (Piet Peters), University of Surrey (Prof. Mike Bader, Caroline Baillie), University of Lisbon (prof. José Dias Lopes da Silva), Courtaulds and ICI. In the framework of this project, two PhD studies were carried out. Muriel Desaeger related the chemical modification of the carbon fibre surface, by an oxidative electromechanical treatment, to the fibre-matrix interface strength. To determine the interface strength and single fibre strength, specific equipment was acquired (nano-indenter) and built (mini-tensile testing machine), and new test methods were developed (the fragmentation test). Jan Ivens used the ongoing work on damage development in laminated composites, including RX and AE, to study the effects of the interface strength on composite strength and damage development.

The Euram project was the start of a decade of high-level, fundamental research on interfaces in composites (which would later be continued as part of the research on natural fibre composites).

TEXTILES

In 1985 at one of the first European SAMPE-meetings (Scheveningen, the Netherlands) Ignaas met some engineers of a Flemish weaving company, Schlegel, who produced carbon fibre brushes using a velvet weaving technique. In this process, two woven fabrics are simultaneously woven and connected by pile fibres that are subsequently cut in half to produce two hairy fabrics. When Ignaas saw both the uncut double layer fabric and the “hairy” fabric, he was struck with two ideas, both related to the improvement of delamination resistance of composites.

The uncut double layer fabric was the ideal textile preform for a sandwich panel where the skins and the core were integrally woven and reinforced with the bridging pile fibres, thus significantly improving skin-core delamination resistance. The first work on the narrow 50 mm wide material of Schlegel was performed over two master’s theses (Yves Bonte 1986, Johan Swaelen 1988).

The results were first presented during a symposium at ESTEC, the technical centre of the European Space Agency in Noordwijk (The Netherlands). Just after Ignaas’ presentation, a young PhD student at Technical University of Stuttgart, Klaus Drechsler, presented exactly the same idea developed in collaboration with the German company Vorwerk. Ignaas and Klaus had never met before and hence had developed the concept of 3D- or sandwich fabrics independently. In 1988, André Delaporte of the Dutch company Parabeam presented similar material but with a width of 1.2 meters, enabling the manufacture of sandwich panels. The preliminary research of Katrien Verbrugge resulted in the Brite-Euram project AFICOSS, the first of a long series of European projects in which Klaus and Ignaas would collaborate (see second chapter).

The “hairy” fabric was also interesting for composites, since delaminations grow easily between the plies of a laminate due to the absence of reinforcing fibres in this matrix rich zone. The hairs on the fabric can provide increased reinforcement of the interlaminar region, by introducing fibre bridging and fibre pull-out, a very important energy dissipating mechanism during delamination growth.

The application of “2.5D” fabrics was the subject of the first patent of the Composite Materials Group (CMG) of KU Leuven, and received the “Innovation Award” of the Techtextil exhibition in Frankfurt (1991). Catherine McGoldrick further studied the delamination resistance of 2.5D woven fabric composites, and her work resulted in a Brite-Euram project on “Improved design methodologies for composite structures” with British Aerospace, MBB, Dornier, Fokker, SAAB, NLR, Imperial College. Vassilios Efstratiou began his PhD research in 1990 within the framework of that project.

In the late 80s, textile composites became a hot issue in composites research, and a more fundamental understanding of their (meso-)mechanics was needed. In collaboration with two other Flemish universities (Ghent and Brussels), the first composite research project funded by the National Fund for Scientific Research (NFWO) was focusing on textile composites.

APPLICATION DEVELOPMENT PROJECTS

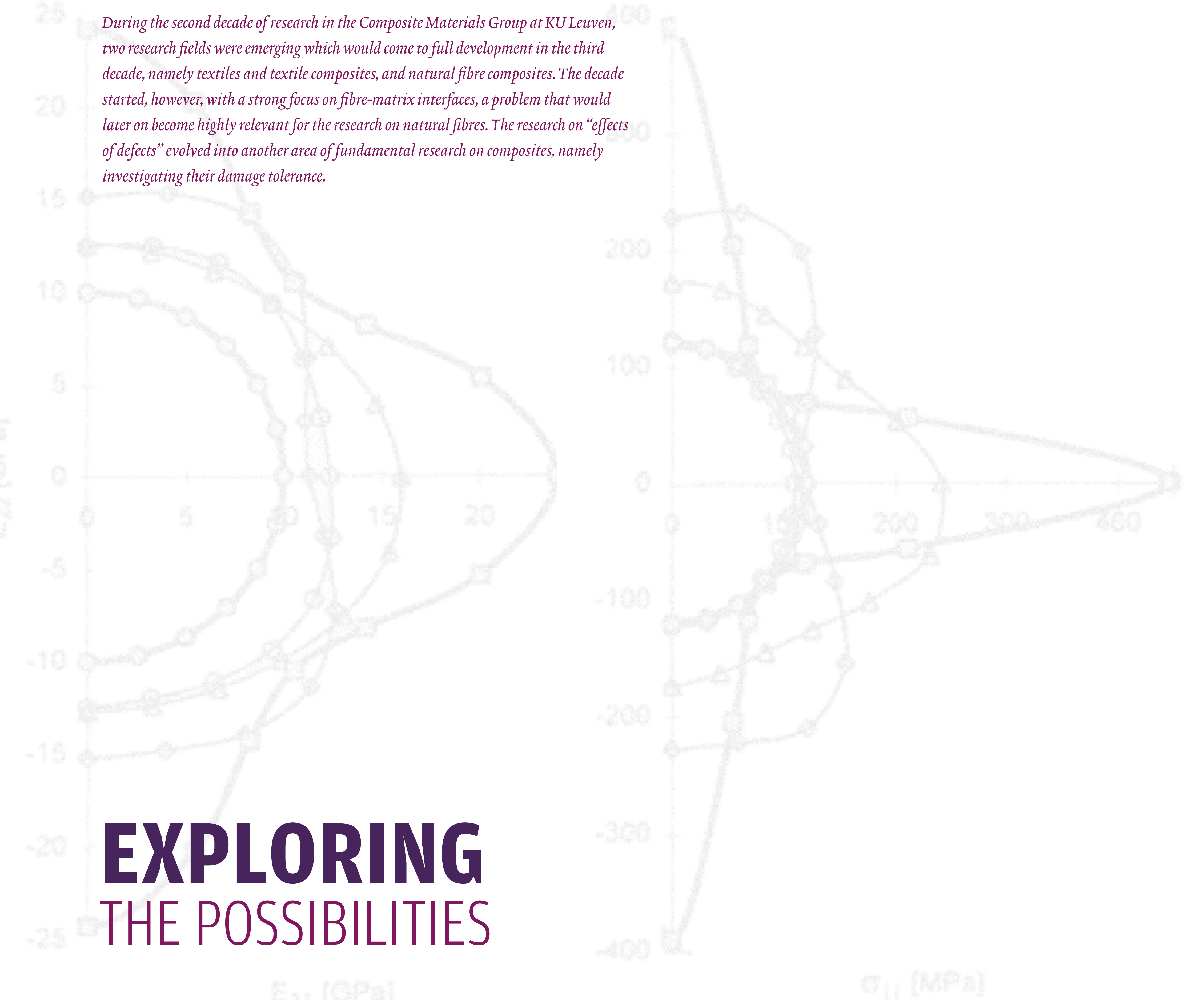
From the very beginning, the research on composites at KU Leuven was strongly linked to local industrial needs. Veldeman, a manufacturer of large tent structures, wanted to replace their large extruded aluminium profiles by lighter composites. A young research engineer, Martin Vandenbussche, together with lab technician Kris Van de Staey manufactured and tested rectangular beams made from glass fibre circular braids and carbon weaves hand–laminated with epoxy resin.
Another local company, Arplam, was supported with technical advice in their attempts to develop a composite glider plane. Friction welding of continuous carbon fibre composites was investigated by Lieve Rutten, unfortunately showing that the distortion of the fibre orientation leads to a significant reduction in mechanical properties.

MOISTURE … AND THE NEED FOR IN-DEPTH TRAINING!

After five intensive start-up years, Ignaas Verpoest felt the need for a time out. A sabbatical (not very popular at that time in KU Leuven) was planned, and Prof. George Springer was kind enough to host him at the Aero/Astro-department at Stanford University.

The effect of moisture on composite performance was, at that time, one of his key research interests. Ignaas could gather some funding from NFWO and from the European Space Agency, combined with a Fullbright grant to finance the stay. His research on moisture in aramid composites resulted in a second “special PhD” (equivalent to ‘Habilitation’ in Germany), defended in 1987. As an exchange post-doc from Stanford in 1988, Tad Doxsee continued the work on moisture absorption. It was finalized by Catherine McGoldrick in 1990.

Ignaas’ sabbatical in Stanford University, and George Springer’s 1988 sabbatical in KU Leuven, were the start of a long series of international exchanges, not only between universities but also with researchers from companies, the first ones being Hans Mooij and Mario Scholle from DSM (The Netherlands).



1990-1999

During the second decade of research in the Composite Materials Group at KU Leuven, two research fields were emerging which would come to full development in the third decade, namely textiles and textile composites, and natural fibre composites. The decade started, however, with a strong focus on fibre-matrix interfaces, a problem that would later on become highly relevant for the research on natural fibres. The research on "effects of defects" evolved into another area of fundamental research on composites, namely investigating their damage tolerance.

EXPLORING THE POSSIBILITIES

UNDERSTANDING MATRIX CRACKS AND DELAMINATIONS

The "effects of defects" research was continued within the framework of several projects, funded by the federal (Interuniversity Attraction Pole IUAP-4 and -5, 1992-2001) and national (Nationaal Fonds voor Wetenschappelijk Onderzoek NFWO) governments, in collaboration with two other Belgian universities, Vrije Universiteit Brussel (Free University of Brussels, VUB) and Université Catholique de Louvain (UCL).

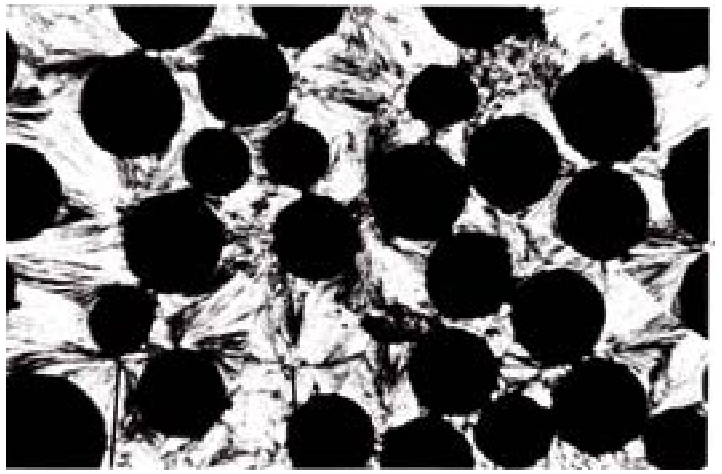
Bernard Goffaux investigated the potential of improving the damage tolerance of composites by using thermoplastic matrices in his PhD thesis. He studied the effect of the matrix morphology of glass-fibre polyamide composites on their interlaminar fracture toughness. This also put our group in a good position to participate in the first round-robin test on mode I and mode II interlaminar fracture toughness testing, together with 17 other laboratories worldwide, coordinated by Peter Davies at L'Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER, France) and Prof. Hans-Henning Kausch at the École Polytechnique Fédérale de Lausanne (EPFL, Switzerland). Bernard also proved that dissimilar thermoplastic composites can be welded under the condition of sufficiently high compatibility between the polymers.

The focus then shifted towards understanding delaminations, for which Philippe Rubbrecht studied the effect of dissimilar fibre orientations on either side of a delamination. The surprising result, unfortunately only published in a SAMPE (Society for the Advancement of Material and Process Engineering) conference paper, was that the G_{Ic} and G_{IIc} values measured for delaminations growing between two 0°-layers (in the fibre direction) are always a lower boundary for the interlaminar fracture toughness between dissimilarly oriented layers, which is the location where delaminations occur in reality!

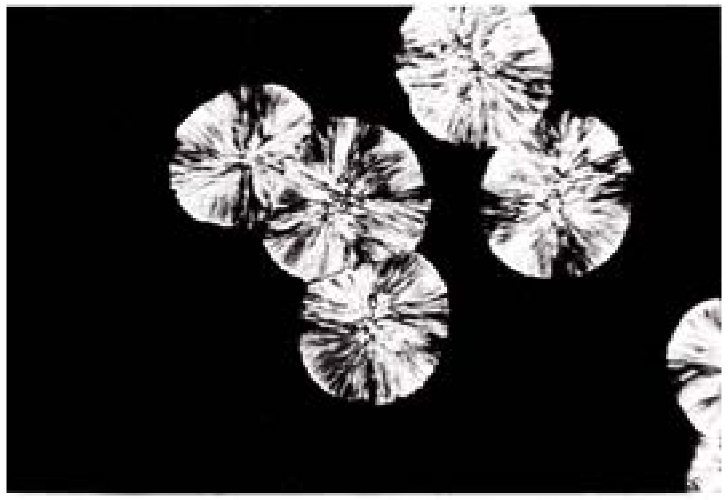
An even more intriguing problem was the interaction between matrix cracks and delaminations. In the PhD-research of Luc Lammerant, a detailed experimental programme was combined with an extensive finite element analysis, in order to find out how, during transverse impact, the crack growth mechanism of cross-ply laminates depends on their lay-up. He was one of the very first researchers who was able to model the interaction between (multiple) matrix cracks and delaminations based on fracture mechanics considerations by the Finite Element Method (FEM). He did this initially for quasi-static loading, and later also for impact loading.

INTERFACES: GETTING DEEPER INTO IT!

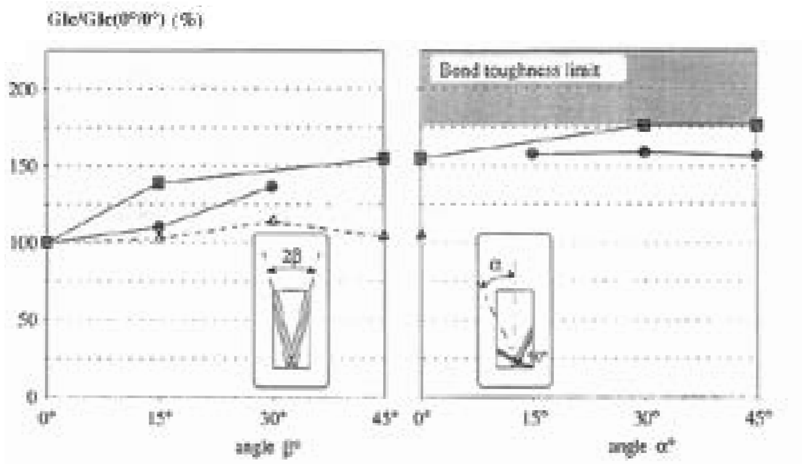
The interface research, initially started in the first decade, came now to full development: Jan Ivens and Muriel Desaeger defended their PhD theses in 1993, and the many, frequently cited papers which resulted from these PhDs prove the high value of the research. We were invited to participate in a worldwide round robin exercise on interfacial test methods, bringing together 12 laboratories, and started a very fruitful collaboration with Prof. Roland Keunings at UCL. Thierry Lacroix, joint PhD student at UCL, developed a more sophisticated data reduction method for the fragmentation test, allowing for a simultaneous determination of the interfacial bond strength and the interfacial frictional resistance.



Crystalline PAA(poly-aryl-amide) reinforced with glass fibres *(PhD thesis of Bernard Goffaux)*

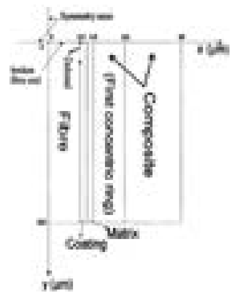


Spherulitic microstructure of PAA(poly-aryl-amide) *(PhD thesis of Bernard Goffaux)*



How the interlaminar fracture toughness depends on the orientation of the layers in the laminate

Comparison between Wu Wei's analytical modeling and FEM-results for the interfacial shear stress at a partially debonded fibre



The complex FE-model developed by Edgard Jacobs to calculate strain energy release rates during interface debonding of 3-phase composites

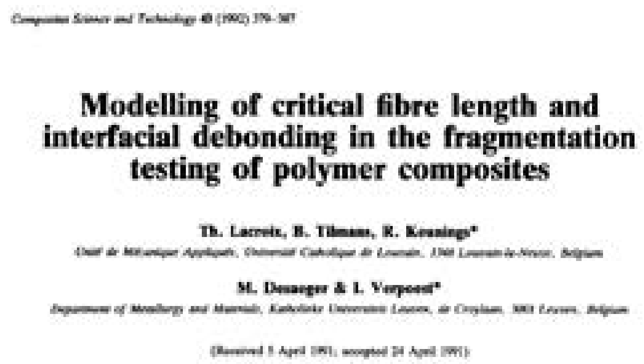
In the same period, collaboration began with Janis Varna (Luleå University of Technology, Sweden), who inspired two new PhD students at KU Leuven, Wu Wei and Edgard Jacobs, to develop even more precise models. Wu Wei improved the variational analysis, initially developed for this problem by John Nairn, based on the principle of minimum complementary energy, for describing the stress transfer around a fibre break in a single fibre embedded in an infinite matrix. He extended the analysis to three phase systems, including a coating in between fibre and matrix

This variational analysis was later generalized, in collaboration with Edgard Jacobs, for a three phase model which included a fibre, a coating with finite thickness, a matrix layer, all this embedded in a composites with "homogenized" properties. Edgard also provided the fragmentation test data of interfacial strength and developed his own finite element model to calculate strain energy release rates for interface cracks in such three phase systems with varying interphase characteristics. Fifteen years later, similar work would be re-started on gradient interphases in steel fibre composites, both experimentally and computationally!

The research of Wu Wei and Edgard Jacobs was linked to a second Brite-Euram (B/E) project on interfaces, more precisely on plasma-polymerised coatings on carbon fibres. It was coordinated by Prof. Frank Jones (Univ. Sheffield), with participation of the Luleå University of Technology (Prof. Janis Varna) and Rheinisch-Westfaelische Technische Hochschule (RWTH, Prof. Walter Michaeli). In the framework of these two B/E-projects, a series of conferences on "Interfacial Phenomena in Composite Materials" (IPCM) was launched by Frank Jones, first held in Sheffield (1989), then in Leuven (1991) and in Cambridge (1993). It later on travelled to Holland, Germany, Hungary and Japan.

Muriel Desaeger stayed on as a postdoctoral researcher for 2 years and guided the research of Torhu Morii, a visiting researcher from Shonan Institute of Technology (Japan) on the effect of interface modifications on the performance of glass mat epoxy composites. It was the start of a very fruitful interaction with the Japanese interface researchers like Prof. Hiroyuki Hamada at Kyoto Institute of Technology.
Jan Ivens also stayed on as a postdoctoral researcher, but shifted to modeling and damage development in sandwich and textile composites.

Ignaas Verpoest visiting the Osaka Municipal Technical Research Centre, with (left to right) prof. Hamada (Kyoto Institute of Technology), dr. Ikuta (Osaka MTRC) and Tohru Morii (Shonan)



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Modelling of critical fibre length and interfacial debonding in the fragmentation testing of polymer composites

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Title page of one of the most cited papers on interface modeling in fibre reinforced composites *(PhD thesis of Thierry Lacroix)*

WEAVING AND KNITTING SANDWICH STRUCTURES

The development of the 3D-woven sandwich materials now continued in a formal collaboration with the Dutch company Parabeam who brought us in contact with the Italian company Metalleido, managed by the brothers Marco and Cesare Fantino. Marco was enthusiastic about the concept and developed a special machine to produce large panels. Through his contacts with the Italian shipyard Intermarine (Gianfranco Fantacci), the Bekaert-owned Spanish company Bremen (Victor Isasi), and Klaus Drechsler's presence at Messerschmidt-Bölkow-Blohm (MBB), we were able to start the first European project on textile composites (AFICOSS), which also included Hexcel (Jean-Pierre Botman), Willems & Van de Wildenberg and Prof. Antonio Miravete of the University of Zaragoza, who Ignaas had met during his sabbatical leave in Stanford University. It was a remarkable combination of very fundamental studies, such as the PhD research of Aart van Vuure, and amazing practical realizations, culminating in the construction of a full size ship hull using the 3D-woven sandwich material.

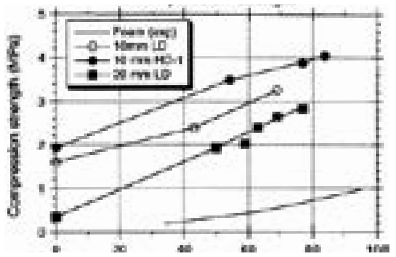
Aart van Vuure investigated the basic mechanical properties of the 3D-woven sandwich structures, their dependence on the pile yarn geometry, and the effect of filling the open core with a foam using a unique foaming technology (for phenolic foams!) developed by Marco Fantino at Metalleido.

A second PhD student, Hermawan Judawisastra, then studied the impact resistance and fatigue behavior of the 3D-woven sandwich structures. Their research allowed us to help Metalleido and Parabeam develop new applications, such as ship decks and train and bus floors (in the framework of a Brite-Euram Value project "multisectorial application and innovation barrier elimination for integral composite sandwich panels," that included several companies like Tencara, Kvaerner, GEC Alstohm and Van Hool). The research also resulted in new sandwich fabrics with 45° pile yarns, high thickness fabrics (up to 70 mm), carbon fabrics and, by the end of the decade, the Australian post-doc Angela Durie succeeded in weaving 45° piles in the warp and weft directions.

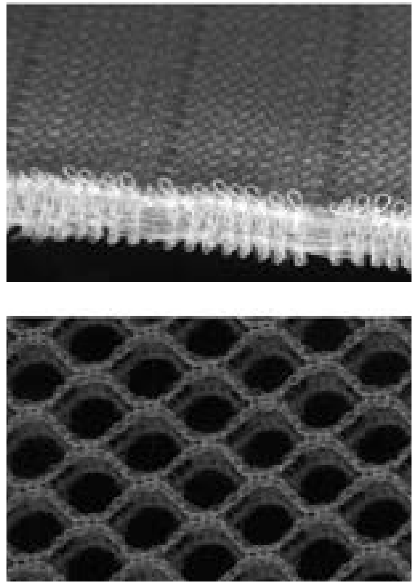
The excellent collaboration in the framework of the AFICOSS project resulted in continued collaboration with several partners, first in the MULTEXCOMP project and the TECABS project.

Inspired by the success of the 3D-woven sandwiches, we investigated the potential of 3D-knitted structures. Via the Flemish composites company IPA, we started a collaboration funded by the Flemish Government, with the company Wydooghe who had just invested in a state-of-the-art "double raschel warp knitting" machine, capable of knitting 3D-sandwich fabrics. 3D-knits have two advantages over 3D-weaves: first, monofilaments are used as pile yarns, so the knit's pile structure "stands" on its own. Secondly, knitting allows a much greater variety of yarn geometries in the skins, from open to fully closed skins.

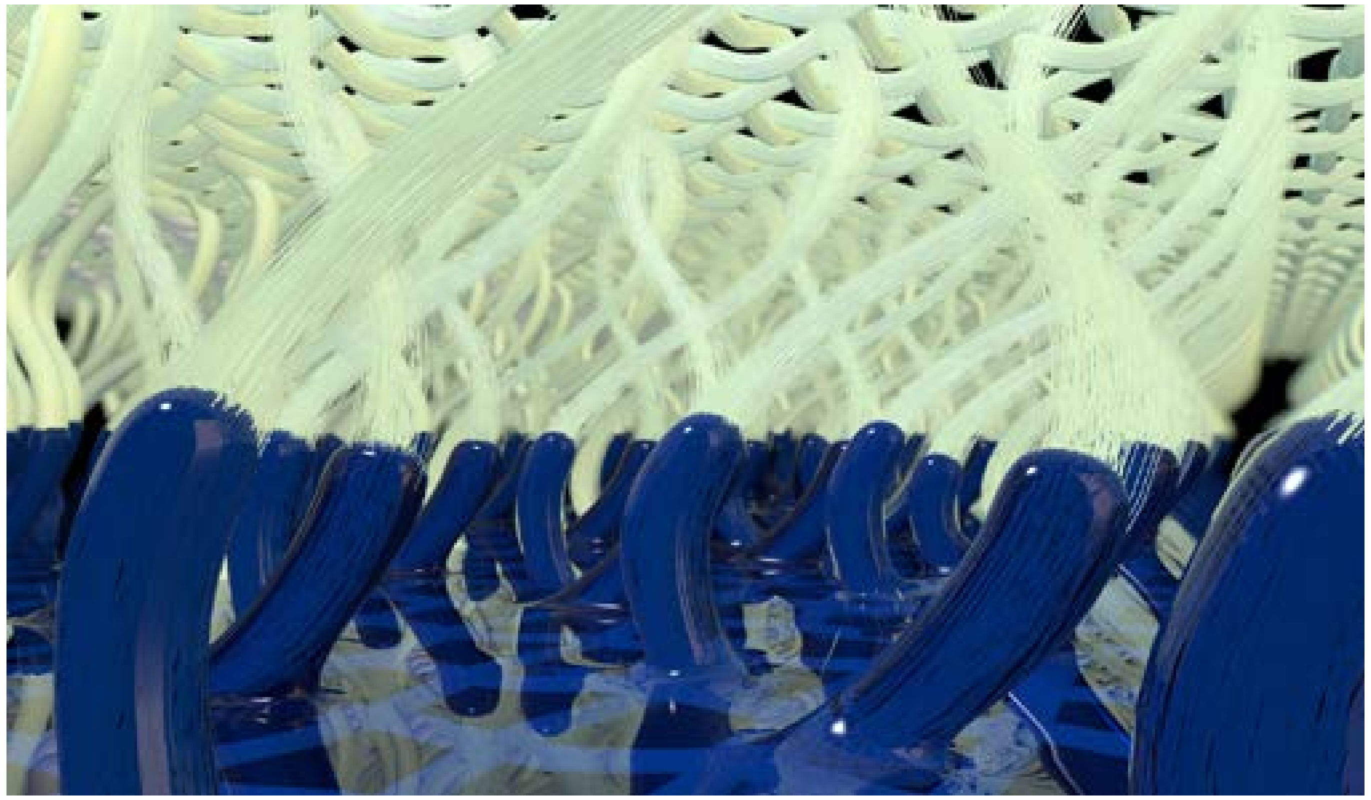
Finally, knits are intrinsically drapable. In order to make a composite sandwich structure, the knit has to be impregnated and hence special multifilament pile yarns (developed by the company Dumont-Wyckhuyse) had to be used. This was just one of the innovations realized in the framework



Effect of foam on the compressive properties of 3D-woven sandwich structures with different pile densities and core thicknesses *(PhD-thesis of Aart van Vuure)*



Open and closed skin 3D knits

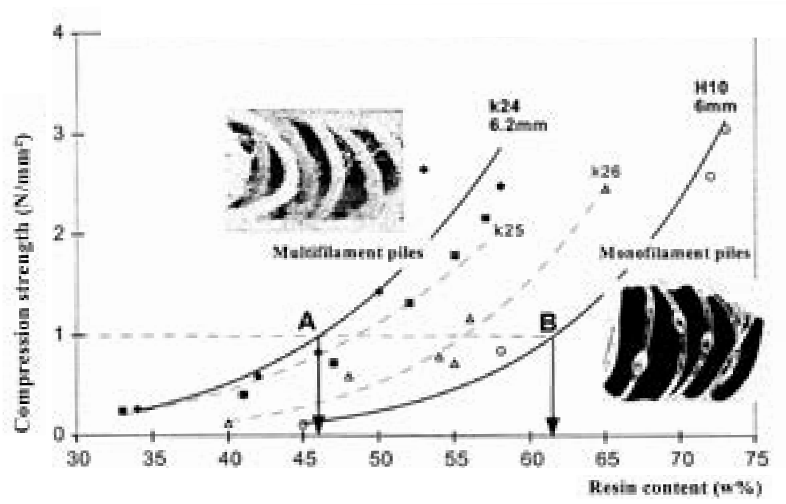


Impregnation of 3D Glass Fabrics

The AFICOSS-partners on the quay of Intermarine, admiring the experimental patrol boat for the Italian financial police, entirely made out of 3D-woven fabric composites

of two consecutive projects funded by the Flemish government and described in the patent on 3D-knitted sandwich structures.
Dirk Philips devoted his PhD research to the processing optimization c these 3D-knitted composites, and to the more fundamental understanc of their mechanical properties. A second patent was filed on the unique combination of a drapable sandwich material, which is stiff and impac resistant, but still open and hence 'breathable'. However, it was not eas convince the composites industry that such 3D-knitted structures have a potential. A Brite-Euram Feasibility Award was granted to KU Leuven, and the companies IPA and Müller Textil, in order to explore the application potential of 3D-knits for composites. Sporting goods like bicycle helme shin protectors, and medical applications like casts and splints have been produced and evaluated (the latter in collaboration with companies like Johnson&Johnson and Smith&Nephew), but without real breakthrough. The patent was finally dropped in 2006.

It would be interesting to analyse in-depth why the concept of 3D-knitted sandwich materials could not be translated into a successful product, and to find the differences with another, yet successful innovation: the continuously produced, folded honeycombs.
Was it a coincidence that Jochen Pflug, a master's student in the EUPOCO-program, had chosen the subject of modeling the 3D-woven sandwich composites for his master's thesis? Probably not, as he was already intrigued by the potential of sandwich structures when he was building a small helicopter with some friends in the Fachhochschule Aachen. Frustrated by the high cost of honeycomb sandwich cores, he was looking for alternatives... but that story will be explained in the next chapter!



Effect of the pile type and resin content on the compression strength of 3D-knitted composites *(PhD thesis of Dirk Philips)*

Ignaas Verpoest and visiting researcher Kazuaki Nishiyabu, experimenting with 3D-knitted casts on their arms!

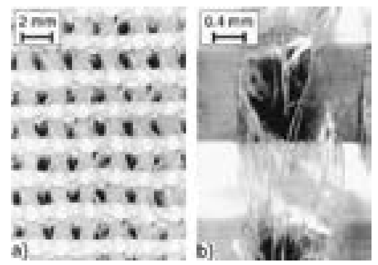
TEXTILES: DISCOVERING A NEW WORLD!

The advantages of the 2.5D-weaves (a neologism that was later on copied by others to indicate *partial* through-the-thickness reinforcements) as composites reinforcement *(see previous chapter)* were proven in the PhD thesis of Vasilios Efstratiou. Depending on the pile density and type of fibres, the interlaminar fracture toughness, and logically also the impact resistance was significantly increased in comparison with 2D-weaves.

This research on 2.5D and 3D weaves and knits opened the door to the fascinating world of textiles. Being a millennia old technology, it was hardly explored by the composites community at the end of the 80s. Our rather 'unusual' approach was quickly noticed by Prof. Tsu Wei Chou at Delaware University and Frank Ko, at that time at Philadelphia School of Textiles, later at Drexel University, two of the leading textile composites researchers at that time. We hence were very happy that they accepted to support our idea to start a new series of international conferences on textile composites TEXCOMP , the first being organized in Leuven in 1992, followed by many others into the new millennium!

In the beginning of the 90s, more textiles were explored for their applicability in composites. A clever idea came to us from Sweden where the company Engtex had been using for some time polypropylene (PP) narrow bands, split films, to produce multiaxial non-crimp fabrics, which are extremely resistant against the dangerous chain saws, used by lumberjacks (there are lots of forests in Sweden). The original idea was to use this technology together with glass fibres so that the PP-strips would become the matrix in a glass fibre – PP composite. Jan Ivens and Mark Van Der Zwalmen of SDE (an engineering company specializing in composite structures founded by Mark and Ludo Van Schepdael - both former KU Leuven students), successfully submitted a European project (1994-1997), involving a team of 14 companies (Saab-Ericson Space, Volvo, Karl Mayer Textilmaschinen and General Electric Plastics among others) and 5 universities (Lund University -Prof. Karl Håkan Anderson, Swedish Institute for Polymers & Fibres -Prof. Roshan Shishoo, TU Hamburg-Harburg -Prof. Karl Schulte, TU Dresden -Prof. Edith Mäder). The large project consortium (19 project partners was very unusual at that time) developed the technology from scratch.

At KU Leuven, the research was performed by Sofie Baeten and Liesbeth Totté, both among the first students of the EUPOCO-master program.



Biaxial preform with glass yarns in warp and weft direction , and split films as binding yarns *(PhD thesis of Sofie Baeten)*

Sofie started a PhD on the processing and properties of this innovative "split film warp knitted" material, proving its potential as a cheap yet performant preform for glass fibre composites. The project also involved the development of fast heating- and cooling molds based on porous metal molds. This innovation came too early on the market and it never became a commercial success, though a few years later, the Twintex textiles, using glass-PP commingled yarns, convincingly showed that there is a need for such preforms, while the search for molds with low thermal inertia for increased production rates is still ongoing!

The research on woven fabric composites with their limited drapability had raised our interest in knits as highly drapable textiles. However, glass or carbon fibre knits were extremely difficult to find. The Flemish company Saturn was able to produce knitted glass fabrics, from which Jo Dendauw produced and tested the first knitted fabric composites in 1992. From 1994, a series of research projects were launched, mainly in collaboration with small and medium sized companies (SMEs) in Flanders: textile companies like Syncoglas, Verdonck-Windhey, Dumont-Wyckhuyse, and composites companies like IPA, Structural and Arplam. It was an interesting experience of combined fundamental (KU Leuven, FWO) and application oriented (IWT, EU-Craft) funding. Nowhere in the world have a larger variety of glass, aramid and carbon fibre knits (both warp and weft) ever been produced and tested, first by Jo Dendauw, later by An Cosaert and several master thesis students.

In his PhD thesis on knitted fabric composite processing characteristics, Yiwen Luo showed that they combine an extremely high drapability (using a biaxial stretching machine that was designed in-house) with excellent permeability (again, using permeability testing equipment developed in-house) and 'tunable' mechanical properties. Indeed, the high versatility of loop structures in knits allows for the degree of anisotropy to be adapted to the needs of the application.

However, knits do not necessarily show the same degrees of symmetry like weaves (orthotropic) or UD-layers (transversely isotropic). Bart Gommers, in his PhD, first explored the stiffness tensors and failure envelopes of this new family of composites and developed new ways to describe them correctly.

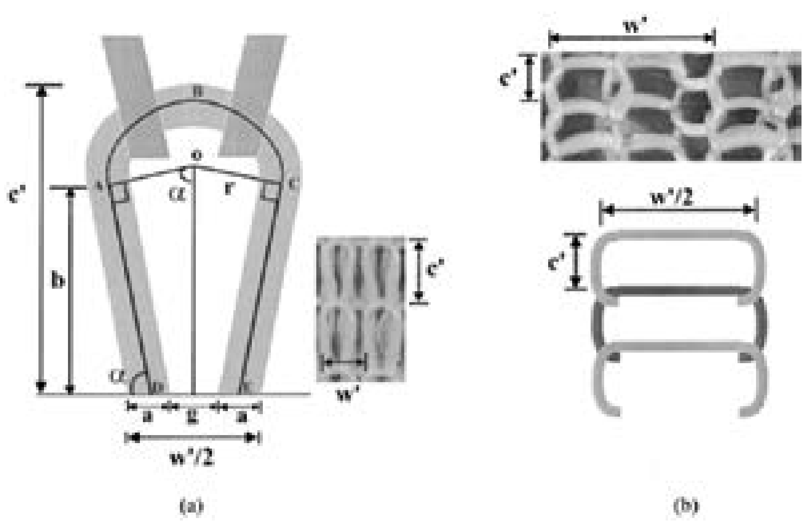
This work further stimulated our interest in modeling the internal structure of textiles in order to understand the influence of the textile architecture on the mechanical properties. Already in 1992, Marc De Vleeschhauwer completed the first master thesis on modeling the behaviour of textiles. Specifically, he worked on the mechanical properties of the skins of the 3D-woven sandwich textiles using a mesomechanics approach, the Fabric Geometry Model (FGM).

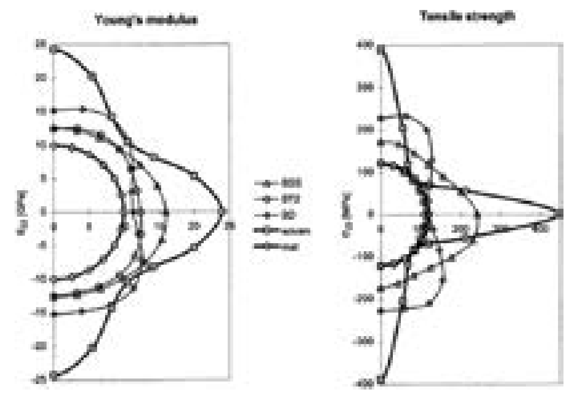
Because of the interest in this modeling work, the next master student on the subject, Philippe Vandeurzen was sent to Drexel University (Prof. Frank Ko) to learn more about FGM in order to apply it to the complex geometry of the skins. Philippe continued as a PhD student, and further refined the fabric geometry model. A strict logical scheme for calculating the full geometry of a general yarn architecture in woven fabrics was introduced. First, a library of 108 rectangular macro-cells has been put together to build complex material unit cells. Next, each macro-cell is divided in a number of micro-cells, containing impregnated fibre bundles, matrix or combinations of both. Then, by a multistep homogenization procedure, and by applying the complementary variational principle, the stiffness tensor of the unit cell as well as the local stresses inside each microcell can be computed. A Microsoft Excel® application was developed to transform the model into a useful design tool.

Because of their more complex internal geometry, knits could not be modeled by this advanced FGM-model. Together with Prof. Paul Van Houtte, who was studying the relationship between microstructure and properties in polycrystalline metals at KU Leuven, it was investigated whether Eshelby-based inclusion models could be an alternative way. In the second part of his PhD, Bart Gommers explored the potential of the Mori-Tanaka scheme, by subdividing the curved yarns in a knit into straight segments, and representing them as transversely isotropic inclusions. This novel modeling approach proved to be very successful, and would be the basis for the later work of Gert Huysmans, culminating in the TEXCOMP-software (see next chapter) developed by Stepan Lomov at the beginning of the next millennium.

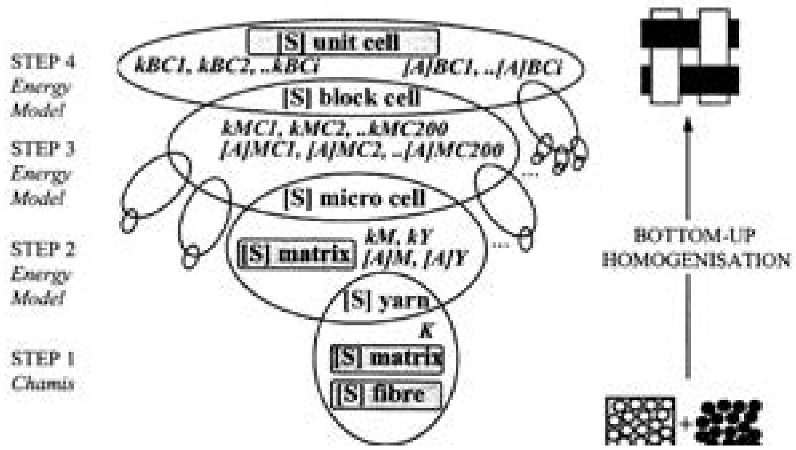
The research on woven and knitted fabric composites resulted in the set-up of the Multexcomp project (1996-1999), where different textile technologies were

Yiwen Luo's model to predict the drapability of knits for composites





Polar plots of stiffness and strength of knitted fabric composites, used in the modelling work of Bart Gommers (see the next chapter)



Schematic representation of Philippe Vandeurzen's complementary energy model for calculating homogenised stiffness and strength of woven textile composites investigated and improved, aiming at the development of high performance composite parts. Daimler-Chrysler (Klaus Drechsler) worked both on the development of n-step braiding and robotic multiaxial braiding, Hexcel (Bruno Bompard) studied the improvement of non-crimp fabrics with minimized yarn distortion, Stoll (Thomas Stoll) worked on the development of weft knitted complex structures with straight inlay yarns, Müller Textil (Peter Rickerl) continued the development of knitted sandwich fabrics, and Aerospatiale Espace et Défense (Georges Cahuzac) attempted to increase the production speed of stitched non-crimp fabrics using the Aerotiss 4/5D technology.

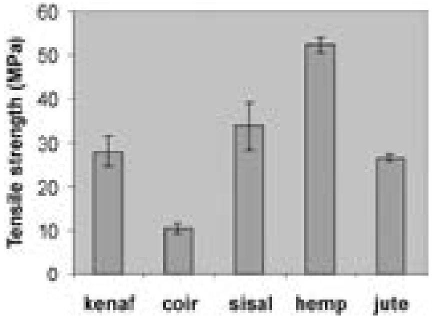
Henk Pattyn and Andreas Prodromou studied and modeled the mechanical properties of composite parts using two or more different textile technologies together. The goal was to evaluate the mechanical, technological and economic performance of these materials. The composite parts were selected and manufactured by Eurocopter (Jean-Marc Bertier), Daimler-Chrysler , Intermarine (Gianfranco Fantacci), Aerospatiale Suresnes and Bistefe (Stefan Van Raemdonck), with the support of Antonio Miravete's group at the University of Zaragagoza. The results showed there is no single textile solution for complexly loaded composite parts and lead to a follow-up project, TECABS, that will be described in the next chapter.

THE STRENGTH AND BEAUTY OF NATURE

In 1995, the idea grew to use strong natural fibres as an alternative for synthetic fibres. Together with IPA (Joris Van Raemdonck), Jan Ivens visited several textile and spinning companies to see if flax fibres could be used. The first flax yarns were supplied by Bentex, a company owned by the brother of Prof. André Deruyttere (former head of department), and the first preliminary results were obtained in 1996 as part of the EUPOCO master thesis of Jan Vervoort.

One of the bottlenecks in the development of natural fibre composites was the influence of the interface, not only the interface between the technical fibre and the matrix, but also between the elementary fibres within the technical fibre. Jayamol George, a post-doctoral researcher from the group of Prof. Sabhu Thomas (M. Gandhi University, Kotaram, India) obtained a junior fellowship of KU Leuven in 1996 and studied the effect of several types of surface treatments (acidic, alkali and diluted epoxy) on the surface morphology and the transverse properties of natural fibre composites.

Simultaneously, two SME-feasibility projects (1995-2000) were obtained for more intensive research and they showed the potential of flax fibres as an alternative for glass fibres in composites: the specific mechanical properties were close to those of glass fibre composites. At the same time, it became clear that fibre damage was introduced by the lengthy decortication (scutching) and refining (hackling and carding) processes. Therefore, a large IWT-project was set up in collaboration with Centexbel (Eddie Baetens) and the Ghent University (Prof. Paul Kiekens, Prof. Marc Stevens) involving several flax companies (Debruyne, Eurolino, Texdem, Profillin, Vanneste), machine constructors (Depoortere and Demaitere), textile companies (Milliken, Dumont-Wyckhuyse, Verdonck-Windhey) and end users (Arplam, IPA, Elco), forming the basis of the PhD of Isabel Van de Weyenbergh (started in 1999). In 1998, we were contacted by Mic Billet and Christophe Cox who had just formed the organization APOPO. Their goal was to train rats (composites research really permeates *every* field!) to detect anti-personnel landmines. In a small house in Deurne they trained rats to detect explosives using their excellent sense of smell. The approach is now successfully used in Mozambique, Angola and Cambodia. Simultaneously, there was a need for body protection of the people accompanying the rats, and in 1999 funding from the Flemish government (DGIS program) was obtained to investigate the possibility of body protection based on natural fibre composites for the PhD work of Paul Wambua, which will be described in the next chapter.



The very first results on (exotic) natural fibre composites *(PhD thesis of Paul Wambua)*

... CONTINUING INTIMATE INTERACTION WITH LOCAL INDUSTRY, TRYING TO FORMULATE ANSWERS TO THEIR NEEDS

Composite materials gradually came into focus by companies using, until then, metals or non-reinforced plastics. The Composite Materials Group at KU Leuven was regularly solicited by the local industry to explore the potential of composites for their products. A few examples are briefly described as illustration.

Raychem had developed a new technology, based on their "shrinkage polymers", to adhesively bond composite pipes. The pipes were tested by Jeanne-Françoise Marsol under combined loading conditions (tension + torsion + internal pressure) and no failure could be observed.
Hannecard, an SME applying rubber and TPU's for technical applications like printing rolls, was interested in exploring the potential of using much lighter composite rolls and sleeves. SDE, Dumont-Wyckhuyse and the textile company Milliken entered the project, in which An Cosaert explored whether glass-fibre thermoplastic preforms could be used. In a follow-up project, we attempted to produce the composite sleeves in one step together with the application of the TPU outer layer.

Several short projects were executed for Arplam, including the design of a composite liner for the repair of large brickwork sewers (together with Prof.

The "African Giant Pouched Rat", trained by APOPO to detect land mines and, more recently, tuberculosis (see www.apopo.org)

Dionys Van Gemert) and the design of signal shacks for the new TGV-railroads. Structural, a company producing pressure vessels for water treatment applications also wanted to replace their thermoset technology by thermoplastics, using a diaphragm forming process developed at IKV-Aachen. Two consecutive projects were submitted, the second one performed by Sofie Baeten, who had returned after working for Daimler Chrysler.
These are just some examples of requests from the local industry to provide them with scientific and technical support in their composite related developments. The number of such requests has gradually increased with the growing know-how within the Composite Materials Group. As it became necessary to provide a structured answer, a "Technology Advisory Service" was devised and is described in the next chapter.

The EUPOCO adventure

As explained in the first chapter, the composites workshops organized at KU Leuven in the 80s proved that there was a need for a more in depth training of engineers in the still new field of composite materials. Both just graduated engineers and employees from companies involved or interested in composites would benefit from it. A difficult balance had to be found between the university education system (semester courses) and the requirements from industry (training sessions of maximum two weeks).

The EUPOCO concept was innovative in two ways. First, it consisted of six modules of two weeks in the first semester and first part of the second semester, followed by a short (3 months) hands-on training in a university or industrial lab; in this way the requirements from both industry and academia were satisfied. Second, EUPOCO wanted to be European, although at that time no framework existed for joint degrees between universities from different EU-countries. Ignaas Verpoest succeeded in bringing together composites research groups from six leading European universities, to elaborate the EUPOCO-program: Imperial College London (prof. Frank Matthews),TU Delft (prof. Theo de Jong and Adriaan Beukers), RWTH Aachen (prof. Walter Michaeli), Ecole de Mines Paris (prof. Tony Bunsell), Université Catholoque de Louvain (prof. Roger Legras, François Dupret and Roland Keunings) and KU Leuven (prof. Martine Wevers, Paula Moldenaers, Gabriel Groeninckx and Ignaas Verpoest). Each of them would also teach at least one course.

An official agreement was signed during an inaugural ceremony by all six rectors of the involved universities at the start of the first EUPOCO-course, the "one year European Master Degree in Polymer and Composites Engineering". The program would be organized successively by the six partners, but the organizational workload made this unpractical and only one semester was organized once by our sister university at Louvain-la-Neuve. To cover the organizational costs, a group of companies sponsored EUPOCO during many years. During the start-up phase, EUPOCO received some funding from the EU COMETT program, and ten years later it was recognized as part of the Marie Curie Training site on composite materials at KU Leuven.

EUPOCO has been attracting during the first ten years more than 200 students, from all over the world, before it would be extended to a 'one year Master in Materials Engineering", having three options: polymers and composites, metals and ceramics, materials for micro-electronics. In 2008, this evolved into a regular two year master degree program, still attracting yearly some 30 students from all over the world.

Prof. Etienne Aernoudt, Dean of the Faculty of Engineering, and prof. Roger Dillemans, rector, signing the EUPOCO agreement on behalf of KU Leuven

Attentive audience during the EUPOCO foundation ceremony.

2000 -2009

GETTING **FOCUSED**

The new millennium in the Composite Materials Group was marked by the consolidation of the research directions, which has shaped the composites research in Leuven ever since. These focused directions are textile composites, natural fibre composites and a new category, process & application development. Later in the decade a new focus on the nano & micro scale also entered the picture.

TEXTILE COMPOSITES

Textile composites were an active research topic in the Composite Materials Group in the previous decade, but this research was broadened and intensified when Stepan Lomov joined the group in 1999.

IMPORTANT SUPPORT OF THE TEXTILE COMPOSITES RESEARCH

The Composite Materials Group's research in textile composites in the early 2000s had important support from national and European public funding sources. The KU Leuven Research Council granted a five year GOA project, followed by a three year OT project (the Dutch abbreviations designate funding instruments for fundamental research) dedicated to the modelling of textile composites. The research was further supported by national funding from FWO (Fundamental Scientific Research Foundation of Flanders) and IWT (Flemish agency for Innovation in Science and Technology). Two consecutive, three-year IWT projects were granted for fundamental research in the interest of the textile and composites industry in Flanders in collaboration with VUB, Centexbel, PMA (Production engineering, Machine design and Automation Division of KU Leuven) and ESAT (Electrical Engineering Department of KU Leuven). These collaborative projects have successfully put textile composites research in the attention focus of the Flemish industry.

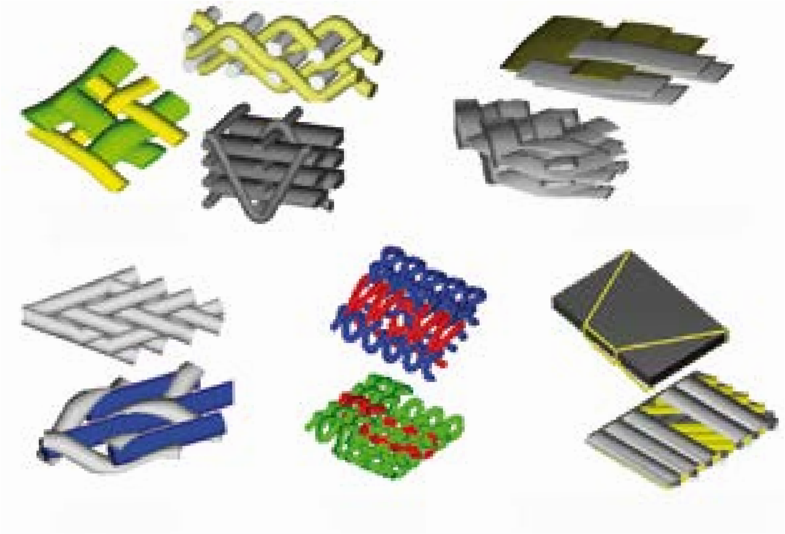
A succession of European projects (AFICOSS – MULTEXCOMP – TECABS – ITOOL) helped to generate the resources necessary for the development of the integrated design tool for textile composites. The first two projects, which ran in the previous decade, established a network of European industry and academia interested in textile composites, with the Composite Materials Group situated as a strong "node" of this network. Dr. Klaus Drechsler (with Daimler at that time) played an important role in these developments.

Stepan Lomov

Stepan Lomov, a professor in St-Petersburg State University of Technology and Design at that time, and Ignaas Verpoest met at a conference in Riga in 1998. Stepan listened to Ignaas' plenary lecture, and specially invited him to his own talk. Discussing afterwards, they found out that the textile models of Stepan ideally fit into the ongoing Composite Materials Group modelling work, started by Bart Gommers and continued by Gert Huysmans, Philip Vandeurzen and Andreas Prodromou in their PhDs. On the spot, Ignaas offered Stepan a ticket to Leuven.

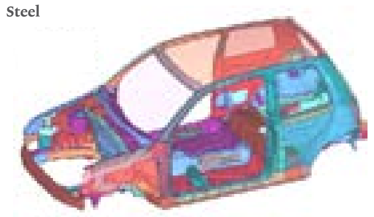
The main attraction of Stepan Lomov's models was their versatility, with a generic algorithm for coding two- and three-dimensional woven structures. Stepan came to Leuven in 1999 as three-month visiting professor, and from 2000 settled in the Composite Materials Group and has led the textile composites research in the group since.

Gallery of meso-FE models based on WiseTex-created geometry

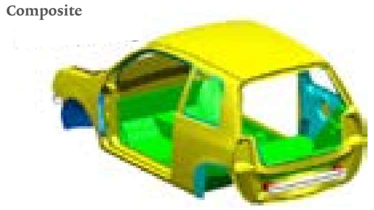


The TECABS project (2000-2004) developed technologies for low cost (heavy tow) carbon composite automotive structures that resulted in a reduction of the 'Body-In-White' weight by 50% and a reduction of the total number of parts by 70% in an A00 type car, while allowing a potential production rate of 50 units/day. TECABS was a collaborative EU research project co-funded by the European Commission under the 'Competitive and Sustainable Growth' programme

Steel



Composite



Body-in-white of the Volkswagen Lupo, used as benchmark in the TECABS project

The third project, TECABS, was a major venture, aiming at the creation of a working prototype of a large composite structural component for a car (the metal floor panel of the Volkswagen Lupo was the comparative benchmark), with an impressive 50% reduction in weight and using textile preforming and Resin Transfer Moulding to achieve a serial production technology. During TECABS, the principles of an "Integrated Design Tool" for textile composites were implemented by the Composite Materials Group in a new software tool, *WiseTex* (see more details further).

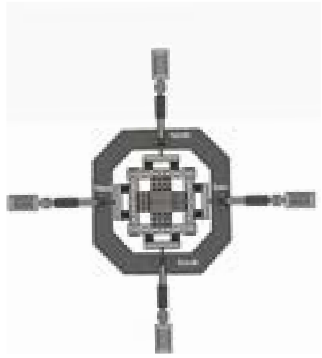
Another hallmark of the TECABS project was the "wide front" of research, combining detailed experimental studies of the textile composite mechanical behaviour (performed by Truong Chi Thanh in his PhD) and manufacturability (deformability of the preform and its permeability during resin impregnation), together with the development of models and software tools. This work was continued in ITOOL, where the same research strategy was applied to aeronautic materials.

The concentrated support for textile composites research from public funds in the first half of the decade can be estimated in total of about €4 million. This effort brought tangible results in the second half of the decade, when industrial funding became a major research resource and shaped the group's work in the field. The wide variety of projects were funded by ASCO, Bekaert, Dow, EADS, Snecma, and Toyota, among many others. The Composite Materials Group became a leading world centre in textile composite research, with a wide front of research covering all aspects of textile composites science and technology, from manufacturing to performance.

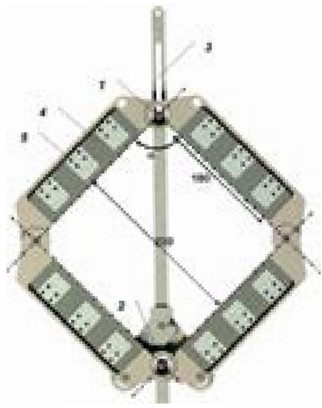
EXPERIMENTAL FACILITIES

The lab development in the new millenium was marked by the introduction of sophisticated, and material-specific methods of measurements. The lab team (Manuël Adams, Bart Pelgrims, Kris Van De Staey, and Johan Vanhulst) under leadership of Jo Mariën was in the centre of these developments.

For mechanical testing of composites, a systematic method of experimental techniques for monitoring the material behaviour and



Biaxial tensile test rig



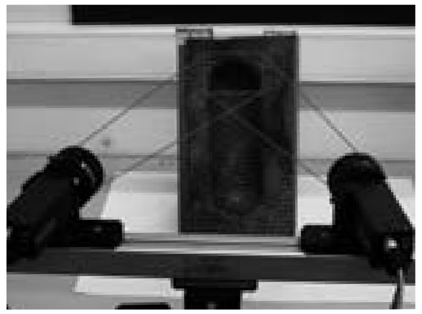
Picture frame test rig

damage development during loading was introduced. This includes such methods as acoustic emission registration, and X-Ray and micro-CT imaging for damage investigation using the excellent facilities created by the Non-Destructive Testing Group (Prof. Martine Wevers). In the PhDs of Surya Pandita, Truong Chi Thanh and Dmitry Ivanov, damage monitoring was extensively used and became a standard element of the experimental protocol in the Composite Materials Group.

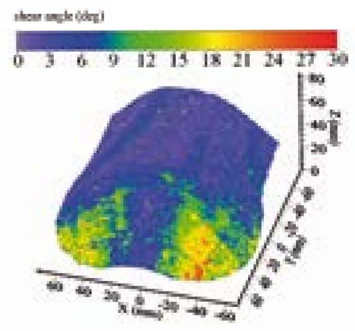
Internationally, the Composite Materials Group was one of the first to broadly apply optical methods in full field strain measurement (Digital Image Correlation) for composites and textiles. Stepan Lomov was active in setting up the CompTest conference series, dedicated to link experimental mechanics using optical methods with simulations of composites. The group is also a member of the OPTIMESS network of Flemish universities.

Important input in the development of optical methods in the Department MTM lab was brought by Prof. Richard Parnas (University of Connecticut), the late Prof. Alan Vautrin (Ecole de Mines St-Etienne) and Dr. Kazuaki Nishiyabu (University of Osaka), who spent their sabbaticals in Leuven. The optical measurements became a routine technique in extensometry for the Composite Materials Group and are applied now on a scale range from microns (strain fields in the matrix between fibres) to meters (strain measurements on the loaded composites parts). Other research groups in KU Leuven, working in such fields as bio-mechanics or civil engineering have also begun to use the equipment and benefit from the expertise of the group.

In spite of the strong orientation on textiles and textile composites research, it was decided not to develop textile production capabilities in KU Leuven, relying on the well-established production facilities of our academic and industrial partners. However, the textile measurement facilities of Centexbel and Ghent University, being fully adequate for garments or carpet industry, did not have capabilities to deal with specific measurements necessary for composite textile reinforcements. Throughout the decade, time and money was invested in the creation of a full experimental "suite" for the characterisation of textile deformability during composite forming for dry textiles as well as pre-impregnated thermoplastic sheets. This includes a biaxial tensile tester (built in the previous decade), a picture frame shear tester, a friction measurement rig and textile compression device.



Optical measurements of the preform shape



Optical measurement of textile reinforcement shear during draping

Ignaas Verpoest, Dirk Vandepitte and Stepan Lomov with the floor pan of a car realised during TECABS project

The developments were done largely in the PhD research of An Willems and Kristof Vanclooster and the Australian post-docs, Angela Durie and Sue Savci, strongly supported these developments in the first half of the decade. The lab is capable of providing a full set of data for the modelling of non-linear forming of composite reinforcements. The group has also developed simulation capabilities for the forming processes using these measurements. The high level of both experimental and modelling work is evidenced by the group participation in the ESAFORM international formability benchmarks, establishing rigorous standards for forming measurements and simulations.

The impregnation of a textile preform by a resin is a process which defines the final quality of the produced part. The impregnation process is controlled by the permeability of the textile – the geometric parameter of a porous media expressing how easily the resin can flow through it. The famous Darcy equation states that the liquid velocity is proportional to the permeability and to the pressure gradient. Measurement of the permeability is not standardised and is a tricky exercise: the difference between the permeability values measured by different methods and in different labs can be as high as two to five times – quite an alarming situation, since erroneous design of the impregnation process leads to the part rejection which is not a small cost for parts like a boat hull or a windmill blade.

A permeability measurement device was built in the MTM lab by PhD researcher Yiwen Luo. The group then closely collaborated with researchers in VUB (Prof. Hugo Sol, PhD researchers Kris Hoes, Gerd Morren) in constructing an advanced automated device in the VUB lab. The collaboration with VUB and with a visiting professor Richard Parnas resulted in the establishment of the variability characteristics of permeability measurements, further investigated in the PhD of Frederik Desplentere.

The interest in the variability of permeability measurements triggered the first international benchmark exercise on permeability, which was initiated by Stepan Lomov together with Bertrand Laine (ONERA). The second benchmark exercise is currently on-going and is aiming ultimately at the standardisation of permeability measurements. The group is also strongly involved in the conference series Flow Processes in Composite Materials (FPCM)– another "invisible lab" uniting scientists around the world.

TEXTILES OF A SPECIFIC INTEREST

Several textile reinforcement families were of special interest to the Composite Materials Group in the 2000s.

Non-crimp fabrics (NCF) are the textile engineering answer to a long-standing challenge faced by designers of composite parts: to combine a waviness-free placement of the reinforcing fibres, with easy, inexpensive, automated manufacturing of the part. Studies of NCF composites started in the TECABS EU project and were further continued throughout the decade and beyond, spanning the manufacturing and performance of NCF composites for aeronautic, automotive and wind energy applications (PhDs of Truong Chi Thanh and Katleen Vallons).

Important results on NCF were achieved by visiting Marie Curie and TEMPUS Fellows, Marcin Barburski and Tsvetelina Stoilova, who studied the NCF deformability, Matteo Vettori who worked on their mechanical properties, and Richard Loendersloot who investigated permeability. FE models of NCFs were developed by David Ranz, Enrico Bernal, Dmitry Mikhaluk and Dmitry Klimshin.

The research was first published in a seven-part paper series in *Composites Part A: Applied Science and Manufacturing* and later summarised in the book "Non-crimp fabric composites: manufacturing, properties and applications" published by Woodhead in 2011, edited by S.V. Lomov.

Research on 3D textile composites started in 1980s with development of woven spaced (or 3D-) fabrics, later produced by the Dutch company Parabeam, and knitted 3D-fabrics, co-developed with several Flemish textile industry partners. In the 90s PhD researchers Aart van Vuure, Hermawan Judawisastra and Dirk Philips studied woven and knitted textile sandwich composites.

Solid 3D-woven fabrics were in the centre of Stepan Lomov's interest during his previous work in St-Petersburg, at that time for ballistic applications and as so-called "clothing", or transport belts, for paper-making machines. In Leuven, he continued this work, now for 3D-textile composite reinforcements.

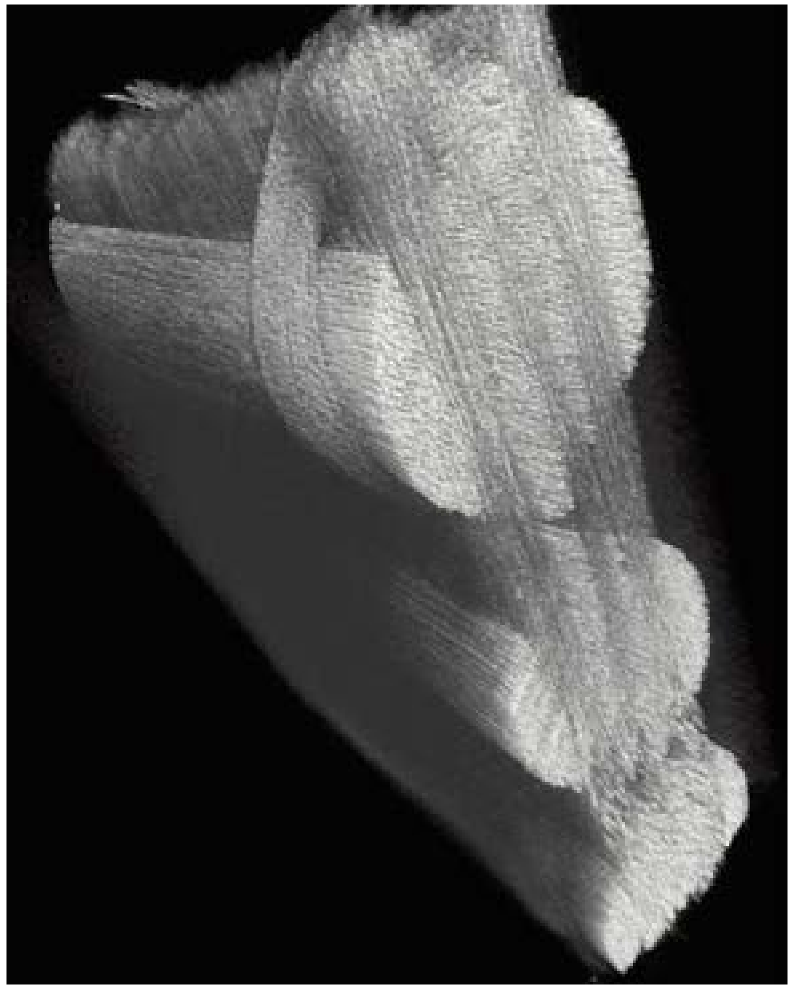
In 2002, a decade-long study was initiated on 3D-woven non-crimp fabrics, produced by the American company 3Tex. The weaving process, invented by M. Mohamed, produces thick fabrics with extremely straight warp and weft yarns (hence the name "non-crimp"), bound together, through the fabric thickness, with thinner yarns. Thanks to the 3D geometry of the reinforcement, the composites reinforced with these fabrics demonstrate extreme resistance to delamination, the absence of fibre waviness provides increased mechanical properties and fatigue resistance, and the thickness of the reinforcement eliminates laminating from the processing chain.

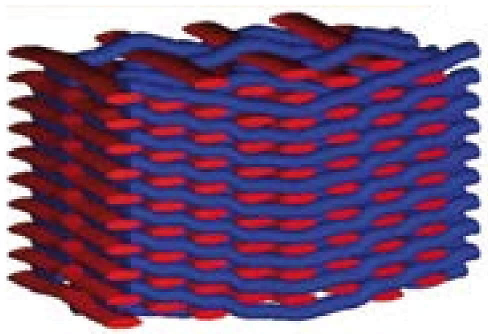
The work in the Composite Materials Group went in collaboration with Dr Alexander Bogdanovich (3Tex and NCSU, USA) and Prof.Valter Carvelli (Politechnico di Milano). Glass 3D-reinforcements were studied first. Frederik Desplentere used micro-CT for his investigation of the internal geometry. A visiting researcher from Uludag University (Turkey) Dr Mehmet Karahan, PhD researcher Dmitry Ivanov, and Erasmus student Guilia Grammelini (Politechnico di Milano) performed detailed studies of damage and fatigue, and a PhD researcher from Politechnico di Milano, Juan Pazmino, investigated the deformability of these 3D-fabrics. Later carbon 3D fabrics and composites with the same non-crimp internal architecture were studied in detail by Dr Mehmet Karahan.

In the second half of the 2000s, the collaborative software development with Snecma (PhD of Guillaume Perie) addressed another class of 3D-woven fabrics, the so-called “angle interlock” for aero-turbine blades. Also 3D, these composites have an internal structure completely different than the 3D non-crimp fabrics. Due to the geometry of the binding yarns, which link together layers of warp and weft from one layer to another, the yarns have high crimp. The fabric architecture creates a “mesh” of interacting yarns, which effectively resists bird strike impacts, preserving the integrity of the blade and preventing further damage in the nacelle (turbine casing). The weaving process for these fabrics allows for variable weft density and an interlacing structure in different positions. This provides the opportunity of designing integrally woven preforms with an optimised composites stiffness.

Apart from textile sandwiches and 3D woven fabrics, Dr Vitaly Koissin studied, in-depth, the mechanical behaviour of structurally stitched composites (ITOOL project). All these developments put the Composite Materials Group on the front line of world-wide research in 3D textiles.

3D woven fabric, micro-computed tomography image





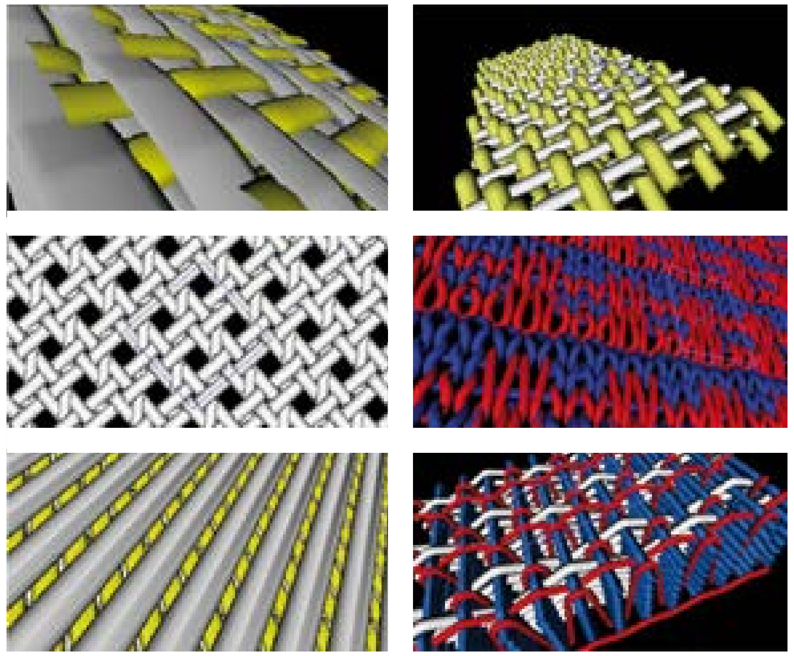
(left) WiseTex model, (middle) an angle interlock 3D fabric, and (right) a turbine blade of Snecma

WISETEX

During the first visit of Stepan Lomov to Leuven in 1999, the WiseTex software project was conceived, aimed at creating a virtual “world” of textiles as they are used in composites. The goal was to find a versatile way to model all types of textile reinforcements for composites – woven, braided, knitted, stitched, 2D, 3D, etc... - to have a general description for all of them. By developing a geometric description of the unit cell, a representative, repeatable element of the textile, the mechanical analysis for the textile itself (deformability and permeability) as well as the composite reinforced with it (mechanical properties and load response) could be modelled. In such a way, an integrated simulation tool could be developed which can serve as a local predictor for the textile and composite properties, which are passed further up the size scale to the macro-analysis of a composite part. The geometrical models of textile were even transferred into virtual reality world (by VRTex software by a visiting scholar Thomas Micolanda).

This concept of an Integrated Design Tool for textile composites, with WiseTex in the centre, was presented during the TexComp-5 conference in Leuven (2000). The paper, “Textile Composites: Modelling Strategies,”

WiseTex industrial and academic licenses worldwide



Virtual reality world: inside a fabric

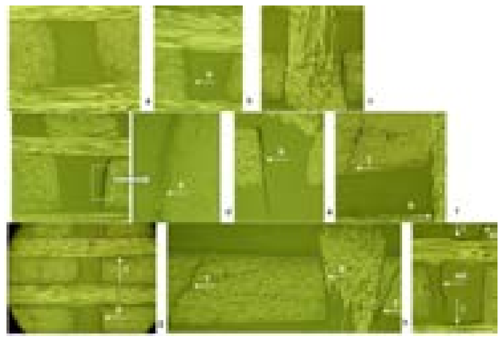
published in Composites Part A, 2001, is one of the most cited publications of the Composite Materials Group. In the master theses of Bjorn Van Den Broecke and Ferruh Tumer, the meso-macro integration of WiseTex was first explored and experimentally validated. This led to the integration of the WiseTex algorithms in the composite simulation packages SYSPLY (ESI Group) and in DIGIMAT (MSC/eX-Stream).

From the very beginning, a decision was made to make the software available commercially (via Leuven Research and Development). This helped in steering the development of a user friendly tool, with graphical capabilities and detailed documentation, establishing the state-of-the-art in the field. More than 40 WiseTex licences have been sold worldwide, and it is used in academia and industry on four continents.

METHOD OF INCLUSIONS

Already in the mid-90s, PhD researchers Bart Gommers and Gert Huysmans were pioneers in the application of the method of inclusions to textile composites. The initial stage of this work was strongly influenced by Prof. Paul Van Houtte, who was using the same method for his work in MTM on polycrystalline metals.

The development of the inclusion-based method ran in synergy with the development of the method of cells, initiated by the PhD of Philippe Vandeurzen in the mid-90s, and continued by Andreas Prodromou. Using the method of inclusions is an elegant "shortcut" for predicting the stiffness of highly organised textile composites, avoiding computationally heavy finite element calculations. Implemented in the TexComp component of our WiseTex software, this method is being applied by various groups worldwide to model woven and braided composite materials. Fast, "on click", TexComp calculations can be effectively integrated in macro-scale structural analysis of composite parts, as it is done in the SYSPLY software of the ESI Group.



Damage in a 3D woven composite, micrographs

RANDOM FIBRE COMPOSITES AND NON-WOVENS

The inclusion-based models were quite naturally extended to the modelling of random, short fibre composites. This work was started in the mid-2000s by a three-year long bilateral project with Dow Automotive. Dr Erika Jao-Jules, supported by visiting researcher from Osaka University, Dr Tetsuya Tsujikami, developed a simulation tool for randomly placed fibres which accounts for the full complexity of fibre orientation and length distribution. Mechanical modelling based on the method of inclusions was advanced in this work to include the non-linear mechanical response of the matrix, and the debonding of the fibres.

The work on random fibre composites was concurrent with studies of the internal structure and mechanical behaviour of non-woven fibrous materials. Dr Amit Rawal contributed to these studies, which were linked to industrial interests (diaper applications of Libeltex company, Belgium). This research direction on random fibre composites was continued into the next decade in collaboration with LMS International in the PhD research of Atul Jain and Yasmine Abdin, advancing it even towards fatigue.

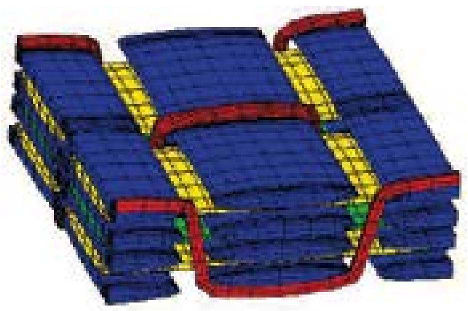
MESO-FINITE ELEMENT ANALYSIS AND DAMAGE MODELLING

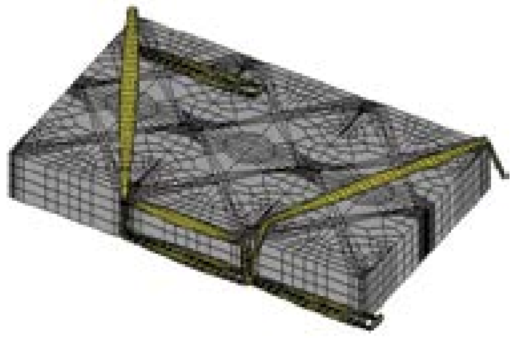
The concept of the Integrated Design Tool, which unified all the work around the WiseTex developments, included important components of manufacturing-related modelling (deformability and permeability of textile reinforcements), and of meso-level finite element modelling of textile composites and damage models.

The early work on meso-FE in the Composite Materials Group was done by PhD researcher Sergey Kondratiev. The development of meso-FE and damage models was strongly influenced and boosted by the interaction with Prof. Masaru Zako and Prof. Tetsusei Kurashiki of Osaka University. Started during Prof. Zako's sabbatical in Leuven in 2002, and the subsequent visit of Stepan Lomov to Osaka, in the second half of the decade the research efforts in meso-FE have been well-structured with clearly identified focal points of unsolved problems. The versatility of the WiseTex geometrical models played a key role in these developments.

The Composite Materials Group was one of the first to recognise the importance of such issues as the interpenetration of yarn volumes in geometrical models and the periodic boundary conditions in case of non-orthogonal unit cells, for example, in braided materials. With the fruitful collaboration with the group of Prof. Masaru Zako in Osaka University (called there simply "Zako-lab"), Dmitry Ivanov developed original approaches to meso-FE modelling in his PhD.

The review paper on "Meso-FE Modelling of Textile Composites: Road Map, Data Flow and Algorithms" (Composites Science and Technology, 2007) which indeed offers a "road map" for the development of meso-FE textile models, is recognised as a milestone in the development of textile FE models. In the same year a symposium on the subject was organised by Stepan Lomov in St-Petersburg. Informal, yet inspiring interactions with Prof. Philippe Boisse (INSA Lyon), Prof. Andrew Long (The Nottingham University) and Prof. John Whitcomb (Texas A&M University) have strongly influenced the





Finite element models of a 3D woven and a non-crimp fabric composite

work in Leuven on this topic. The spirit of openness of the research and free exchange of ideas and approaches has created a strong international community in the narrow field of finite element modelling of textiles.

Modelling of damage in textile composites was started in the Composite Materials Group in the work of Gert Huysmans, Philippe Vandeurzen and Andreas Prodromou, and was based on inclusion and cell models. Models for damage initiation and propagation were implemented in meso-FE of textile composites by Dmitry Ivanov in his PhD. He has identified a serious drawback in the widely used stiffness reduction approach – namely, non-physical predictions of propagation of the damage zone under shear loading – which was further explored in collaboration with Dr Larissa Gorbatikh and Stepan Lomov. This has led to the implementation of more detailed, continuous damage variable algorithms – an approach now accepted in the majority of meso-level damage models for textile composites.

The damage modelling work in the Composite Materials Group was strongly supported by experimental damage monitoring using in-situ acoustic emission and digital image correlation. Acoustic emission identification of damage thresholds during mechanical testing became a routine practice in the lab. Optical registration of strain fields with sufficient resolution to reveal the variability of the strain inside the textile composite unit cell, together with "post-mortem" observation of cracks, provided effective experimental data for the validation of the damage model.

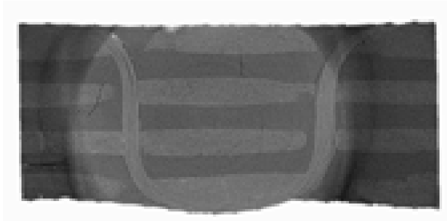
FATIGUE

Fatigue of steel wires was the topic of Ignaas Verpoest's PhD, and the fatigue of fibre reinforced composites was studied in the PhD of Martine Wevers, the first PhD in the Composite Materials Group. The group's established experience in fatigue and the technical fatigue lab facilities built over the years were utilized extensively in the 2000s and applied to advanced textile composites.

In her PhD, Katleen Vallons made detailed fatigue studies of carbon non-crimp fabric (NCF) composites for automotive applications, in collaboration with Toyota. In her post-doctoral work, Dr Vallons continued to study NCF composite fatigue with glass NCF reinforced composites for wind mill blades in collaboration with Owens Corning.

The fatigue of structurally stitched carbon composites for aeronautic applications was investigated by Dr Vitaly Koissin and a Master student Vanni Tomaselli, in collaboration with Prof. Valter Carvelli (Politecnico di Milano). The detrimental effect of the stitching on the fatigue life was investigated in depth by damage monitoring during fatigue.

Dr Mehmet Karahan, in collaboration with Dr Alex Bogdanovich (3Tex and NCSU, USA), Prof. Carvelli and Erasmus master student Guillia Grammelini, made in-depth studies on fatigue of 3D-woven glass and carbon composites. They definitively proved that the absence of fibre waviness improves the composite fatigue resistance. Juan Pazmino, a Master student from Milan, studied fatigue in 3D-braided composites produced by 3Tex (Alex Bogdanovich), under supervision of Valter Carvelli and Stepan Lomov. At the end of the decade, Larissa Gorbatikh investigated the influence of nano-reinforcements on the fatigue behaviour of textile composites.



Fatigue cracks in 3D woven composite, micro-CT image

By the end of the decade, this experimental work had created a rich database of fatigue data on textile composites. In parallel, detailed investigations were performed of damage development in the same materials during static loading. In 2009 (at the SAMPE-Europe conference in Paris), based on these accumulated observations, Stepan Lomov formulated the hypothesis that a relationship exists between the damage initiation thresholds under quasi-static loading and the fatigue limit for glass and carbon reinforced textile composites.

At the end of the decade, fatigue studies of textile composites have been advanced to modelling. Started by Prof. Satoshi Hanaki (Hyogo University) during his sabbatical in Leuven in 2007, fatigue modelling was continued in the PhD research of Jian Xu. This project ran in collaboration with Prof. Joris Degrieck and Prof. Wim Van Paepegem (Ghent University), and was based on meso-FE damage analysis of textile composites developed in the Composite Materials Group and on the "fatigue jump" concept elaborated by Prof. Van Paepegem.

MODELS OF TEXTILE DEFORMABILITY AND PERMEABILITY

Models of textile deformability were developed and implemented in WiseTex by Stepan Lomov. The textile-mechanics based WiseTex models provide a shortcut for approximating the compression, shear, and tensile resistance of textiles. In the following decade, the meso-FE analysis of dry textile deformability was started in the group.

Forming modelling – the calculation of the deformation of a textile reinforcement sheet during forming on a 3D mould – was started in the group in the PhD of An Willems, co-guided by prof. Dirk Vandepitte at Mechanical Engineering. The important decision was to develop our own material models for Abaqus, rather than using specialised "closed" forming software. An Willems' work benefited from close collaboration with Philippe Boisse (INSA Lyon). It was important that An, aside from developing the algorithms and writing the code, made major improvements in the group's experimental facilities (biaxial tester and picture frame) and especially in the method of optical analysis of the strain fields of a textile during its deformation. This significantly improved the quality and precision of these non-standardised measurements.
Kristof Vanclooster continued this modelling work in his PhD by investigating the difficult case of the collective forming of a laminate. He built a special device for measuring the frictional interactions between the plies at elevated temperatures. Constant participation of the Composite Materials Group in annual ESAFORM conferences (Stepan Lomov is a member of the Scientific Committee of the composite forming section) facilitated the integration of the group's work in the world-wide research community, substantiated by participation in the international forming simulation benchmark exercise

Permeability models in the WiseTex suite were introduced first by Dr Eugene Belov. Due to the suggestion of Prof. Richard Parnas, the Lattice Boltzmann method of Computational Fluid Mechanics was chosen at this initial stage. With exploratory algorithms developed by Dr Belov, the FlowTex component of the WiseTex suite was created by Ir Teo Peters (Department of Computer Science, KU Leuven) under supervision of Prof. Dirk Roose and Stepan Lomov.

Flow lines during impregnation of a woven composite

The high computational cost of the Lattice Boltzmann method, in spite of its proven predictive capabilities, led to further adaptation to a finite difference solver of the Navier-Stokes equations. In the PhD of Bart Verleye, under guidance of Prof. Dirk Roose and Stepan Lomov, this approach was implemented in FlowTex. This was possible thanks to an intensive collaboration with the group of Prof. Michael Griebel at the University of Bonn. The computational efficiency of FlowTex allows for the calculation of the homogenised reinforcement permeability in a few seconds, allowing the integration of the meso-level permeability modelling with macro scale impregnation simulation, the latter using the local permeability values as input to the Darcy equation solver.

A comparative analysis of the permeability algorithms was carried out by Bart Verleye in collaboration with Prof. Andrew Long at the University of Nottingham. The permeability modelling work was "embedded" in the international community the same way as in the case of formability – via the conference series Flow Processes in Composite Materials (FPCM) and the benchmarking exercise initiated via this conference.

The TOTEM of Jan Fabre

In the year 2000, at the occasion of its 575th anniversary, -the Katholieke Universiteit Leuven was founded in 1425-, KU Leuven wanted to express its gratitude for the fruitful cooperation with the council and the inhabitants of the town of Leuven. The famous Belgian artist Jan Fabre was invited to create a sculpture that would be placed in the middle of one of the main squares of Leuven, directly opposite the Central Library of the university.

Jan fabre created a, in the meantime iconic, sculpture: a beetle, a scarab, pinned up to the sky. Quoting from the book that was edited at that occasion: "Beetles are at the centre-stage in Jan Fabre's work. … In Fabre's universe the beetle is no dead, earthbound insect, but rather an image of change and rebirth. As once in ancient Egypt, the scarab is a symbol of transience and new life. The beetle is also a protagonist in Fabre's interest in that form of science that dares to go beyond the boundaries of its discipline and shapes new theories through a fertile crossover".

The 3 meter long beetle would be placed on a 25 meter high stainless steel needle, in the middle of the Ladeuze Square. An additional problem was raised

by the fact that the structure had to be placed on the ceiling of the underground parking, which was constructed without having the placement of this heavy but slender needle in mind. Piet Phlips, architect at the technical services of KU Leuven, invited prof. Guido de Roeck from the Civil Engineering Department and Ignaas Verpoest, to provide technical assistance in the concrete elaboration of the plans.

Prof. De Roeck developed detailed finite element models to simulate the dynamical behaviour of the tall needle, with on top the mass of the beetle, not a favourable design (hence, the beetle should be as light as possible). Also the stress concentrations around the eye of the needle and at the mounting flange on the concrete ceiling of the underground parking have been calculated and optimised.

Ignaas Verpoest has than evaluated the composites design and manufacturing method of the beetle, as proposed by Remie Bakker from the Dutch company Manimal Works. Bakker first sculpted, based on the designs of Jan Fabre, a rigid foam model capturing all the details of a real scarab. Then a negative mould was made. Inside the mould, first a weather resistant polyester gel coat was applied, upon which layer by layer the glass fibres and the polyester matrix were applied. For critical parts, it was suggested to use carbon-aramid hybrids or even unidirectional carbon rovings, at the attachment points of the wings or at the flanges where the beetle was joined to the stainless steel needle, 20 meters above ground level. It is clear that there was a big concern about strength and durability of the structure, but the geometry of the beetle was so unique, and the time pressure so high, that Remie Bakker preferred to rely on his own experience and the advice of KU Leuven's composite experts, instead of waiting for detailed model calculations.

Ten years later, after many heavy thunderstorms, cold winters and (some) hot summers , the beetle is still pointed to the air, " as an indication of a place where scientists and artists are driven on by the same desire to understand something that cannot (yet) be grasped."

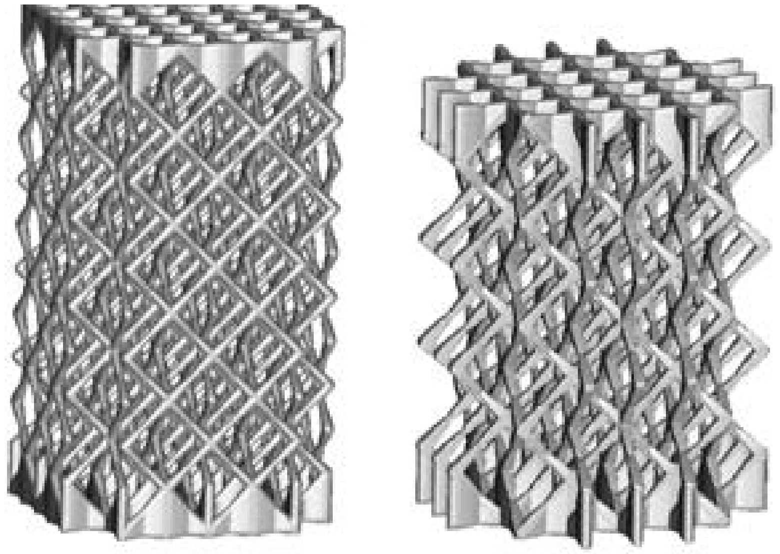
BEYOND FIBRE REINFORCED COMPOSITES

Fibre reinforced composites were not the only class of heterogeneous materials in the focus of the Composite Materials Group attention. In mid-2000s, bone and bone scaffolds became the subject of modelling (PhD of Maarten Moesen) and experimental (PhD of Greet Kerckhofs, supervised by Prof. Martine Wevers and Stepan Lomov) studies, in close collaboration with the bio-mechanics group in the Mechanical Engineering Department (Profs Jos Vander Sloten, Hans Van Oosterwyck, Harry Van Lenthe) and the NDT group of the Department MTM (Prof. Martine Wevers).

Maarten Moesen developed mechanical models for bone and bone scaffolds, treated as a general open cell porous media or a space lattice. This led him to the optimisation of the bone scaffold geometry, based not only on mechanical, but also on biological/medical requirements. For this, the relationship between the surface strain and the behaviour of osteoblasts and osteoclasts on the surface were used. The optimised scaffolds that were developed were produced using the rapid prototyping technique in collaboration with Dr Jan Schrooten.

Greet Kerckhofs started her PhD-work (co-guided by prof. Martine Wevers) with a seemingly straightforward exercise: the comparison of the porous scaffold geometry measured using micro-CT (μCT) and micrography on the material cross sections. This problem proved to be rich in scientific considerations, and the research progressed to the establishment of an experimental protocol for μCT measurements of porous materials. During her PhD work and in her post-doctoral period, Greet Kerckhofs was a key specialist for the development of the μCT facilities in the Department MTM, measurement techniques, and scientifically sound processing of the μCT data. The work on porous materials, both in modelling and μCT measurements, continued in the next decade in the PhD research of Oksana Shishkina and Bart Buffel.

Bone scaffolds generated using the beam network based strategy
(PhD thesis of Maarten Moesen)



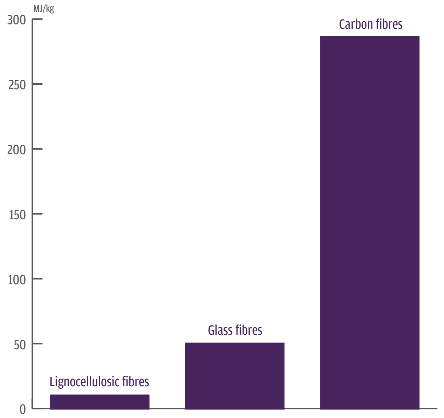
RESEARCH ON BIO-COMPOSITES

IMPROVING FLAX FIBRES FOR COMPOSITES

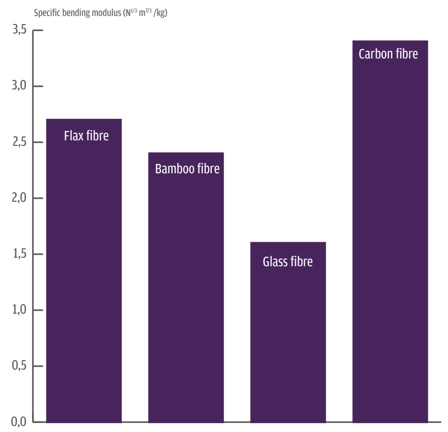
In the new millennium, the natural fibre research that had started in 1995 further developed into an important research line in the Composite Materials Group. Flax fibres played a central role from the start. Despite the numerous advantages of natural fibres in comparison with glass fibres (low density, bio-renewability and CO2-neutrality, reduced health risk and good specific mechanical properties), some bottlenecks were detected when implementing flax fibres in composites. Fractographic studies had shown significant fibre damage due to the lengthy retting, decortication and refining processes.

The first IWT-project (1999-2001) was focused on identifying the optimum fibre processing conditions for composite applications. During her PhD study, Isabel Van de Weyenberg found that fully retted flax with minimal mechanical processing provided better reinforcement, yet the transverse properties remained poor, indicating the need for surface treatment.

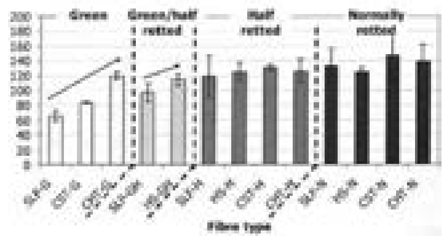
A second IWT-project IMPRONAFI (2003-2005), involving Ghent University (Prof. Joris Van Acker), IPA, Tex-Dem, Depoortere, Arplama and Stavelse, was specifically aimed at improving the impregnation and the fibre-matrix interface. Isabel applied alkali and silane treatments to improve the interface strength, which she investigated using the microdroplet test, revitalizing the interface research of the nineties. The results of IMPRONAFI project were further exploited by the project partners, and led to the patented flax-epoxy prepreg technology of Lineo which is now being used in various sports articles like tennis rackets.



Energy needed to produce various fibres; natural fibres need much lower energy/kg than glass and carbon fibres



Specific flexural modulus for various fibres; flax and bamboo fibres outperform glass fibres and approach carbon fibres, making them very suitable for lightweight structures loaded in bending



Tensile strength of UD flax/epoxy composites. The data are grouped per retting degree of the flax reinforcement *(PhD thesis of Isabel Van de Weyenberg).*

Aart Willem Van Vuure

Aart Willem van Vuure joined the CMG in June 1991 as a PhD student, after graduating as Chemical Engineer with a specialization in polymers at the University of Twente (Netherlands). His PhD concerned the characterization of woven sandwich-fabric composite panels, including aspects of foaming, vibrational behaviour and modeling the sandwich core properties with finite elements. He also performed a study on composite recycling.
After his PhD in 1997 he joined a Drexel University (Philadelphia) spin-off company to develop knitted wheel wells for an electric vehicle. From 1999 till 2004 he worked at Unilever Research in the UK to develop hair products, based a.o. on polymers and structured fluids (rheology work). He also analysed the tangling (knotting) of hair fibres.
In 2005 he re-joined the CMG as a technological advisor on composite materials for Sirris (50%). In the other 50% of his time he built up a research portfolio, which was soon focused on natural fibre composites and later also on bio-polymers. He was also involved in other research projects like the Thermhex thermoplastic honeycomb project, the development of a new resin system with Huntsman, various developments with Deceuninck and initiated a project on fine steel fibre composites with Bekaert. For Sirris, he managed to expand the technological advisory role to a 100% position in 2007, which meant a colleague could be hired. The Sirris activity has since further expanded and in 2009 the Sirris Leuven-Gent Composites Application lab (SLC) was founded.
In 2012 he finished his last paid commitments for Sirris and took on a 50% lecturer position at GroupT Leuven Engineering College, combining this work with his coordinating role of the bio-composites research in the CMG.

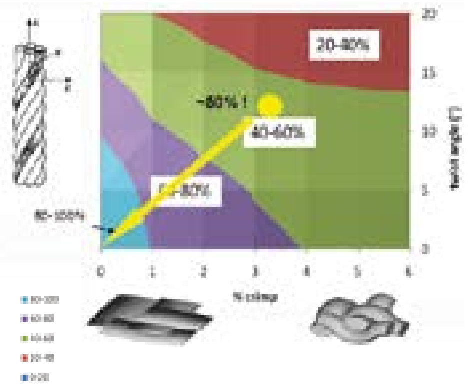
NATURAL FIBRE COMPOSITES: CAN THEY BE USED FOR IMPACT RESISTANT COMPOSITES?

Paul Wambua investigated the possibility of using natural fibre reinforced thermoplastics for low-cost ballistic body protection within the framework of the DGIS project with APOPO, described in the previous chapter. Paul studied a wide variety of natural fibres (coir, hemp, flax, jute, kenaf, and sisal) in non-woven and woven form, in combination with polypropylene, subjected to static, impact and ballistic testing. Flax composites exhibited better ballistic properties than jute and hemp composites, and both optimised flax composites and hybrid composite/steel components were found to be effective against secondary fragmentation resulting from detonation of blast mines containing up to 150 grams of C4 explosives. Paul, who finished his PhD in 2004, is the author of the Composite Material Groups most cited paper to date (667 citations as of June 2013).

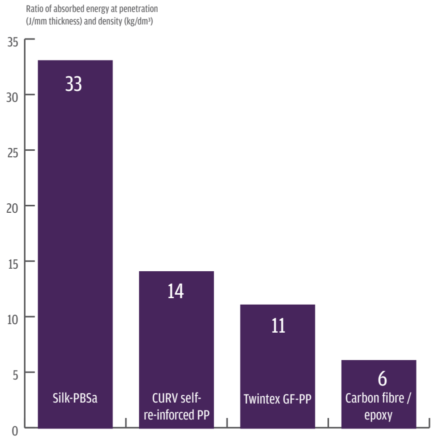
FLAX FIBRE COMPOSITES GET A BOOST; COOPERATION WITH CELC

Beginning with the first projects on flax fibres, the Composite Materials Group has nurtured good contacts with the flax industry. The results of the first projects, and a crisis in the textile industry, made the flax industry look toward composites for new growth opportunities. CELC (the European flax and hemp confederation) strengthened this interest in 2006 by starting a technical section devoted to the technical (or non-textile) use of flax and hemp fibres. The main task of CELC is the promotion of flax and hemp fibres in all potential markets. Because of a lack of technical knowhow about composites in the flax industry, it was decided to start a collaboration with the Composites Materials Group. From 2009, this has resulted in the assignment of a 50% consultant in the group, to support the CELC in technical issues, a position taken up by Joris Baets. A European Scientific Committee was founded, chaired by Ignaas Verpoest and with 8 members from 5 different countries: prof. Joris Van Acker and dr. Joris Baets (Belgium), prof. Hans Lilholt (Denmark), prof. Christoph Baley, prof. Moussa Gomina and dr. Peter Davies (France), profs. Jörg Müssig and Gerhard Ziegmann (Germany) and prof. Mark Hughes (Finland).

In this collaboration, the task of the Composite Materials Group is to give technical advice on the application of flax and hemp fibres in composites in order to correctly communicate the potential of these fibres to the composites industry, and hence to strengthen the promotion actions of CELC in technical markets. The Composite Materials Group also represents CELC in dedicated events like the yearly JEC composites tradeshow, and helps CELC members in adapting their processes to meet the requirements for application in composites. Exploratory research, conducted in the framework of master theses at KU Leuven, has indeed confirmed that the



Combined effect of yarn twist and fabric crimp on modulus of woven flax fibre composites; typical fabrics give only 50% of what is possible for straight fibres



Impact resistance of silk fibre composite with high strain to failure matrix, as compared to various other composite materials, normalised to material density

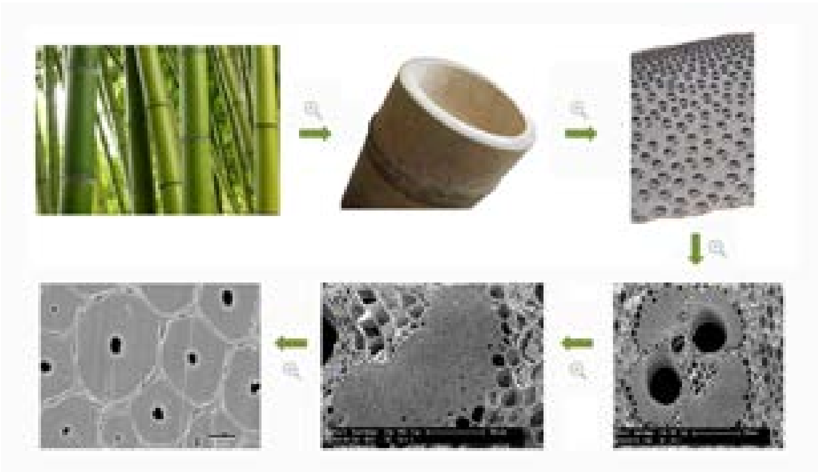
current textiles are not optimized for application as composite preforms. Yarn twist and fabric crimp should be reduced as much as possible, an effect which is more important than in glass fibre composites because of the low transverse and shear properties of natural fibres. The results of these studies have been communicated clearly to the flax industry, and the development of appropriate flax preforms was started immediately (see results presented in the next chapter).

SILK FIBRE COMPOSITES

In 2005, designer and silver-smith, Nedda El-Asmar, who had followed one of the workshops organised in the framework of the first Composites-on-Tour initiative, approached the Composite Materials Group with the idea to explore silk fibre composites. Preliminary work by Master's students Karen Wolnik and Jan Vanderbeke showed the potential to make composite materials with very high impact resistance, particularly when combined with high strain-to-failure matrices. A bilateral project was set up with Hermès (2006-2008), executed by Jan Vanderbeke, which led to a patent on impact resistant silk fibre composites. Upscaling the compression molding process for this innovative composite was started with Eire Composites, but has now been on hold for some years.

BAMBOO FIBRE COMPOSITES

In 2005, two Columbian Master's students, Lina Osorio and Eduardo Trujillo, joined one of the last sessions of the EUPOCO program. During their studies in Columbia, they had developed mechanical extraction principles to obtain high quality, undamaged, technical bamboo fibres from the bamboo culm. This work also earned them a Belgian Development and Cooperation price. Their EUPOCO Master's thesis work focused on the performance of the fibres in composites and showed the great potential for bamboo fibres as a fast growing alternative for glass fibres.
In the meantime, a cooperative project had been set up with Vietnam, sponsored by the Belgian government through BelSPO. Vietnamese



Bamboo from culm to fibre

Extracted and cleaned bamboo fibres with length equal to the inter-nodal length of the bamboo stem; both processes have been mechanised; (far right) The supply chain of coconut fibre in full operation; coconut fibres are an important, cheap local fibre source in countries like Vietnam

partners were Hanoi University of Science and Technology (HUST, Prof. Bui Chuong) for research on bamboo fibre composites and Cantho University (CTU, Dr. Truong Chi Thanh) for research on coir (coconut) fibre composites. Initially, Nele Defoirdt was employed in this project, but she later went on to finish her PhD at the University of Gent. Lina and Eduardo also got linked to the BelSPO project and in 2008 they spent one year back in Columbia, sponsored by BelSPO, to construct a prototype extraction machine for the bamboo fibres. The process they developed is still unique in the high quality of the bamboo fibres obtained. They then returned to Belgium to start their PhDs in 2009.

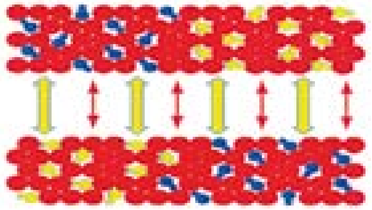
JUTE AND COIR COMPOSITES

In 2004, a project sponsored by VLIR (Flemish Inter-university Council, funding collaborative projects with developing countries) was set up in cooperation with Bangladesh, to support their local research on jute fibre composites. In the framework of this project, a range of equipment was transferred to the labs of BUET (Bangladesh University of Engineering and Technology). In a later stage, toward the end of the six-year project, three Master's students along with a PhD student, Rashnal Hossain (2009-2011) were seconded to Leuven for intense collaboration work. Rashnal is currently finalizing his PhD in Bangladesh. Jute fibres are a low-cost alternative natural fibre with an intermediate modulus around 35 GPa. The analysis of the fibre and composite properties is particularly interesting due to the relatively large lumen size (about 20%) of the fibres which needs to be correctly accounted for in mechanical models.

In 2009, Le Quan Ngoc Tran arrived as a PhD student on a grant from the KU Leuven International Research Office linked to the above mentioned BelSPO project to work on coir fibre composites. Coir fibres are particularly interesting because of their very high strain to failure (on the order of 30%), which means that they have the potential for energy absorption. Ngoc has confirmed this functionality during his PhD. His research was specifically focused on the interfacial aspects of coir fibre composites (see next section).

INTERFACES IN NATURAL FIBRE COMPOSITES

Around 2007, it was decided to explore the physical-chemical aspect of the mechanical approach which had traditionally been used to characterize interfaces, thus linking mechanical adhesion strength to the chemical groups present on fibre and matrix surfaces.



Schematic of acid-base interactions at composite interface; hydrophobic groups interact through van der Waals forces; polar groups interact with the oppositely charged species of the other material

This work got a big boost by two PhD grants which were granted to Tran Le Quan Ngoc (KU Leuven International Research Office grant) and Carlos Fuentes (special IRO grant based on a cooperative agreement with Peru). Operating as an effective duo, they set up a comprehensive physical-chemical-micromechanical approach to study interfaces in composites. The basic approach is the matching of surface energy components on both sides of the interface. Ngoc focused on coir fibres and Carlos on bamboo fibres.

A good cooperation based on joint publications was set up with Prof. Christine Dupont at Université Catholique de Louvain. Initially, before a single fibre tensiometer could be purchased by the MTM Department, contact angle measurements were performed at UCL. More recently, UCL performs chemical characterization of surfaces by XPS (X-ray Photo-electron Spectroscopy). This approach is especially relevant for thermoplastic composites and has already helped to select suitable thermoplastic matrices for bamboo and flax fibres.

BIO-BASED MATRICES: TOWARDS FULLY BIO-BASED COMPOSITES

In 2000, Philippe Willems (Amylum) and Jan Ivens made the first attempts to produce natural fibre reinforced composites based on starch. Although they were able to produce both stiff and more flexible biopolymer plates, the moisture content of natural fibres caused difficulties in the processing of natural fibre based biocomposites, and after the departure of Jan Ivens, and a change in research strategy at Amylum, the preliminary research was stopped. Shortly thereafter, an exploratory study on wheat gluten as a bio-polymer was performed in cooperation with Prof. Jan Delcour of the Bio-engineering Faculty. The work was led by Dara Woerdeman, post-Doctoral researcher from the USA and led to a patent in 2004 on modified gluten biopolymers with improved toughness.

In 2009, based on the patent of Dara Woerdeman, a so called Platform project from the KU Leuven Industrial Research Fund (IOF) was started to further investigate the toughening of gluten biopolymers and to explore natural fibre composites with a gluten matrix (PhD of Nhan Vo Hong). This project is in cooperation with various groups at KU Leuven, in the Bio-Engineering Faculty (Prof. Jan Delcour), Chemical Engineering Department (Prof. Peter Van Puyvelde) and Chemistry Department (Prof. Bart Goderis and Prof. Mario Smet). So far, modified gluten properties have matched these of epoxy resins and very promising results have been obtained with flax fibre reinforced gluten and gliadin (the low molecular weight fraction of gluten).

WOOD POLYMER COMPOSITES

Since 2007 the Composite Materials Group has worked in close cooperation with Deceuninck Plastics. The collaboration started with research to improve the impact resistance of wood polymer composites with a PVC matrix, executed by Tom Houthoofdt who was seconded from Deceuninck to KU Leuven. A combination of measures to improve wood-PVC adhesion (based on physical-chemical analysis) and to lower the PVC viscosity, led to more than a 50% increase in toughness. The cooperation with Deceuninck has since proceeded on fibre rod reinforced window frames and low density PVC foams.

Ignaas Verpoest demonstrating the lightness of the Cosmolite suitcase *(picture by Rob Stevens)*

PROCESS AND APPLICATION DEVELOPMENT

REACTIVE THERMOPLASTICS

In the 2000s, the interest in thermoplastic composites was rising because of their thermoformability and recycling possibilities. The main issue in the production of continuous fibre reinforced thermoplastics is that the extremely high viscosity of thermoplastics makes it difficult to impregnate textiles. One of the solutions is to use a reactive prepolymer. This low viscosity prepolymer can be processed into composites in the same way as a traditional thermoset: infused with low viscosity, and because a catalyst is added, it can react (cure) into a thermoplastic after infusion.

In the PhD of Hilde Parton (financed by a FWO grant) the possibilities of CBT (cyclic butyleneterephthalate) for this process (*in-situ* polymerization) were investigated. This PhD research was part of the European project AMITHERM, in which the potential of in-situ polymerised thermoplastics was proven at KU Leuven by the manufacturing of a leaf spring for an experimental car. Mould and injection equipment were developed jointly with German and Swedish project partners, the injections were successfully realised by the technical staff at KU Leuven (Jo Marien, and Manuël Adams)

The PhD of Hilde revealed that the polymerized CBT does not have the same properties as traditional PBT. The failure strain of the polymerized CBT was about 2% (while PBT is around 200%). The main reason for this was determined to be a different crystal structure due to the *in-situ* polymerization. This was shown by WAXD and SAXS measurements at ESRF (Grenoble) in collaboration with Prof. Bart Goderis (Chemistry department).

The former master student of Hilde, Joris Baets, was motivated to solve this problem, and started a PhD (financed by an IWT grant) on the topic. By changing the processing parameters or chemical modification, the crystal structure could be manipulated. This indeed led to a higher failure strain of polymerized CBT, which gave this material a 'real' thermoplastic (tough) behaviour.

SAMSONITE SUITCASE

In 2003, the Composite Materials Group at KU Leuven was contacted by Arno De Taeye, vice-president of Samsonite, to discuss the advantages composite materials might offer for application in suitcases. This was the start of what would become one of the most exciting R&D-projects, in which materials inventions, process innovations and product design would go hand in hand and develop simultaneously.

The requirements for an ideal suitcase material sounded rather simple: light and resistant to impacts at low temperatures *(when your suitcase is* *unloaded from the cargo bay after a transatlantic flight*). Lightness is no problem for any composite (with glass, carbon, aramid...even natural fibres), but they are intrinsically brittle and hence not usable for suitcases. Exploring different alternatives, we found the newly developed "self-reinforced composites", which just came available on the market: the Pure® material developed at Eindhoven University and commercialised by Lankhorst (at that time) and the Curv® material developed by prof. Ian Ward at Leeds University and commercialised by BP-Amoco (now Propex).

A comparative study that was carried out at KU Leuven showed that the Curv® material offered a superior combination of mechanical properties and processing characteristics. In this material, polypropylene films are highly stretched, slit into tapes and woven. This weave is then compacted at a precise temperature so that only the outer few microns of the tape are melting, providing the matrix for the self-reinforced composite. The high degree of stretching creates a strong molecular orientation in the tapes, and is responsible for both the high stiffness (compared to 'normal' PP) and high impact resistance, even at low temperatures.

However, at that time, not a single real product had ever been made with this new material, and certainly not a product with the doubly curved shape of a suitcase shell. During the first project, carried out by Wouter Broeckaert at MTM together with prof. Dirk Vandepitte at Mechanical Engineering and funded by IWT (Flemish government, 2004-2007), the focus was hence on the development of the matched die compression moulding process. This was particularly complex because the highly oriented, stretched tapes want to contract again when brought to the high temperature for compression moulding. Initial experiments were carried out on the big HACO-press at KU Leuven and then transferred to a specifically built prototype press at Samsonite (resulting in a patent).

The whole exercise was a challenging example of 'concurrent engineering', because three developments had to happen simultaneously. First, the materials had to be adapted to the process and to the end-user requirements so the initial composition and lay-ups of the Curv® material had to be changed drastically. Second, the compression moulding process had to be adapted to the shrinkage behaviour of the Curv® material, but also to the specific designs developed by designer Maxime Szyf. The result was the X-LITE suitcase, remarkable in its attractive design, but even more extraordinary in its performance, realising an unmatched combination of toughness and lightness.

After the commercial launch of the X-lite, already in 2005, the Composite Materials Group at KU Leuven continued to collaborate with Samsonite on further improvement of both the material and the process. This resulted in the Cosmolite suitcase (2008), having a more 'rounded' design that fits better to the specific processing characteristics of Curv®, but also allowed us to further reduce the thickness of the shell, resulting in "the strongest and lightest Samsonite ever." The advertisements proving the extraordinary impact resistance became a hit on YouTube, and Cosmolite quickly became the best selling Samsonite ever, reaching a volume of more than half a million suitcases per year by the end of the decade.

(Left) **The first Samsonite made from the Curv® material: the X-Lite and** (right) **Samsonite's newest and lightest composite suitcase: the FireLight**

INCREASING PRODUCTIVITY WITH SNAP-CURING RESINS

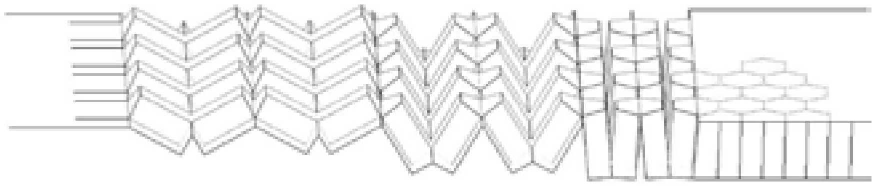
One of the bottlenecks in the manufacturing of thermoset composites is the lengthy curing times resulting in slow production rates unsuited for mass production applications such as in automotive parts. Researchers at Huntsman Polyurethanes in Everberg (Belgium) developed a polymer chemistry enabling "snap cure," having a very short time between gel and cure of the resin, with minimal cure shrinkage and peak exotherm. Moreover, the new resin system exhibits a high temperature and fire resistance.

Eric Huygens contacted Ignaas via his neighbor Jo Mariën, and in 2008, a bilateral collaboration was set up with IWT-support. Kelly VandenBosche and Marcel Bruijn optimized the "HTS" resin, in collaboration with the Huntsman specialists, for composite manufacturing in resin transfer molding, prepregging, casting, compression molding and resin infusion. During the collaboration, Marcel moved from the department MTM to Huntsman, providing the perfect technology transfer.

DESIGNING AND BUILDING A REAL AIRCRAFT PART!

The IWT-funded project with ASCO (Belgium) is an example of a longer term (three year) project, which supported the company in their "education" in design and production of carbon fibre reinforced parts for aeronautic applications. ASCO is a well-known producer of metal (aluminum, titanium, steel) parts for airplanes. During the project, the team of ASCO specialists under coordination of Stein Janssens, with the support of KU Leuven partners (Profs Dirk Pandepitte, Ignaas Verpoest and Stepan Lomov and researcher Francesco Loribbio), have completed the development of an important load-carrying part: hinge arm in a wing. This included a stress analysis and complete redesign of the part (the final design was quite far from the metal prototype), as well as manufacturing and testing of the final part (in collaboration with VUB). The entire team was satisfied, when, during the full-scale testing of the part, the acoustic emission, optical and thermal measurements all registered the real onset of damage just after the load level predicted by the stress analysis!

(Left) **The hinge arm developed in collaboration with ASCO;** (right) **The bearing tested till failure**



The production principle of the Thermhex thermoplastic honeycombs: vacuumforming half-hexagonal shapes, then longitudinal folding.

While writing his aerospace engineering thesis, Jochen Pflug worked in a German helicopter company on the design, calculation and production of a composite sandwich structure with a Nomex aerospace honeycomb core. During this work he gained an awareness of the high cost and the difficult production process of traditional honeycomb cores on one hand, and the excellent mechanical properties at low weight on the other hand. Encouraged and fascinated by this experience and the potential of lightweight materials, he followed the European Postgraduate Education in Polymer and Composites Engineering at the KU Leuven.

At that time, a continuously produced textile sandwich material (3D-woven sandwich fabrics) was being investigated in the Composite Materials Group. During his master thesis Jochen Pflug investigated the properties of this material. The first idea to produce honeycombs through a continuous folding process emerged during this time, and resulted in a patent application in February 1996 for "FoldHex."

The further development of those first ideas was strongly encouraged by Ignaas Verpoest and in the summer of 1996, an agreement to share patent costs and income was made between KU Leuven and Jochen Pflug. In 1997 Jochen joined the Composite Materials Group as a PhD student, to further develop folded honeycomb materials and production processes. Starting in 1998, the feasibility of the folded honeycomb concept was investigated in a two-year IWT research project, funded by the Flemish government *(partners included Hexcel and Assidomän, now Kappa)* to which also the Mechanical Engineering department of KU Leuven joined (prof. Dirk Vandepitte).

In July 1998, an exclusive license agreement for paper based packaging applications on the FoldHex patent was made with the company AssiDomän Packaging (now Kappa packaging). During the feasibility project, two improvements of the FoldHex concept were invented (and patented), namely the TorHex folded honeycomb from corrugated cardboard and its production process, as well as the thermoplastic folded honeycomb concept ThermHex.

The first innovation was further explored in the TorHex project, again funded by IWT, and strongly supported by Assidomän / Kappa as a foreign partner. Several versions of lab scale machines (with narrow width) were developed and constructed, proving the potential of the technology. The step towards a full width prototype machine remained too large, however, despite the interest of other companies like Recticel, who envisioned applications in automotive interiors.

A large sheet of Torhex paper honeycomb

In the meantime, the ThermHex concept had been further elaborated, again on a small scale. This allowed for the start of the first ThermHex project (2002-2004), again funded by IWT, and with three types of (Flemish) industrial partners: material producers (Mondi, Libeltex, both providing skin materials), automotive companies (Toyota Motor Europe and Johnson Controls) and finally Polyvision, producing white boards. Lab scale machines were designed and built for the vacuum forming of the half hexagonal cells and for the subsequent folding of those cells onto one another, forming the honeycomb core, proving the great advantage of this unique continuous core manufacturing process.

As a final step towards industrial implementation, a second Thermhex IWT project (2004-2005) was launched, with the same local industrial partners. Four foreign partners could be added as the project obtained a Eureka-label: Kaysersberg and Rieter as Tier1 suppliers to the automotive industry, Toyota's Japanese supplier Kawakami, and Arcelor-Mittal.

During these projects it became clear that the ThermHex technology was ready to cross the border between lab-scale and prototyping. For achieving this, larger equipment and more money was needed, but the industrial partners also asked for a clear long term plan.

Two actions were taken in parallel: the ThermHex and TorHex demonstration lines were built (Oct 2004 to Oct 2005), and installed in KU Leuven's Innovation & Incubation Centre (IIC), so that larger samples could be produced. Simultaneously, Jochen Pflug, Ignaas Verpoest and Dirk Vandepitte, strongly supported by KU Leuven's tech-transfer office LRD, started exploring the possibilities of a spin-off company, by developing the legal structure and looking for venture capital.

By the end of 2005, the company ECONCORE was officially founded, but already in spring of 2005, Econcore was present at the JEC exhibition in Paris. Jochen Pflug became the CEO, Ignaas Verpoest and Dirk Vandepitte joined the board, while Tomasz Czarnecki joined as an engineer. Econcore's business model was focused on selling licenses of both the ThermHex and TorHex technologies, while at the same time further developing and improving the processing lines, and proving the superior performance to cost ratio of these continuously produced honeycomb cores. In 2007, Econcore moved to a new location with a larger production hall at the science park of KU Leuven in Haasrode. In 2008, further innovations resulted in a new patent for a half-closed honeycomb core, which could be produced from PP, PET, PC and PA films.

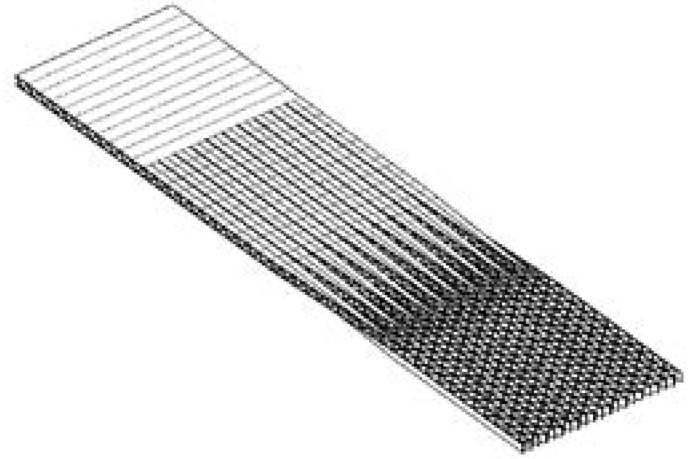
The first licensee (2008) was the Japanese Itochu group, and their company Gifu Plastics producing business-to-business packaging solutions, which was an unexpected application. The fully PP-based sandwich panels are commercialised under the trade name Teccel. One year later, Econcore decided to start its own production facility 'ThermHex Waben' in Halle, Germany, in order to fulfil the demand for medium sized orders or larger prototyping volumes.

The licensing strategy of Econcore proved to be successful: in 2010, the Italian company Cartonplast (now Karton) acquired a license and is commercialising the ThermHex sandwich panels under the trade name Exalite, followed in 2011 by Renolit (Italy) producing Gorcell, a PP-core and PP-wood fibre skin sandwich panel, mainly for automotive applications.

In the meantime, Econcore won the Bioplastics Award of 2010 for a fully PLA-honeycomb sandwich panel. Later on, new material combinations were developed, like a fully lignin-based sandwich panel.

In 2012, the first USA licensee was added, the Chicago based company Coroplast, while Tata Steel (UK) acquired a license for metal skin honeycombs, based on the ThermHex core technology. In 2013, the Turkish company Röplast signed a license agreement, and most recently Toray and Itochu entered into a license option agreement on honeycombs made from Toray's high impact polyamide Nanoalloy®.

Econcore's unique honeycomb technology is now used in eight production lines in three continents (2 in Japan, 2 in Italy, one in Germany, Turkey, UK and USA).



The production principle of the Torhex paper honeycombs: longitudinal sliting of a corrugated cardboard, then rotating over 90°

Teccel foldable boxes made by Econcore's licensee Gifu Plastics in Japan

ThermHex panels, produced by Econcore and its licensees

Answering the industrial needs for support: TAD and SLC

The previous chapter showed the growing number of requests for scientific and technical support from local industry. Two initiatives were undertaken to meet these growing demands.

The first initiative was forming the Leuven Composites Processing Centre (LCPC). This virtual lab assembled all the composite processing related research of KU Leuven. LCPC consisted of researchers of the Composite Materials Group (Ignaas, Jan Ivens and Sofie Baeten) and the departments of Chemical Engineering (Prof. Jan Mewis, Prof. Paula Moldenaers and Inge Vinckier), Chemistry (Prof. Gabriel Groeninckx and Wendy Loyens), Mechanical Engineering (Prof. Rik Van Brussel, Prof. Dirk Vandepitte and Mieke Lossie) and Civil Engineering (Prof. Dionys Van Gemert). The goal was to provide single counter access to all of the composites knowhow of the KU Leuven, thus lowering the threshold for industry to approach the university and to stimulate collaboration in the field of composite processing.

The second initiative was the creation of a "Technology Advisory Service" (TAD), a service largely financed by IWT and linked to a collective centre (similar to the TAD of Prof. Marc De Bonte on surface technology in the department MTM). A TAD-service supports companies in finding answers to short term problems and questions, either through direct intervention, or by acting as a go-between. The TAD also organizes seminars and workshops on topics of interest for the composites industry. An application for a TAD on composites was prepared in collaboration with Herman Derache, Guy Fryns and Umberto Baraldi of WTCM-CRIF (now called Sirris) and submitted to IWT. After the approval, Jan Ivens became the first Technology Advisor for the composites industry in 1999, focusing on assisting companies in the transition from open to closed mould manufacturing. After his departure to industry in 2001, Mieke Lossie took over the advisory service, followed by Bart Vangrimde who was Technology Advisor from 2001 to 2004. After Bart joined Sonaca, Aart Van Vuure took over in 2005.

Still, the demand for short and medium term projects supporting the local industry was growing, and surpassed the capacity of one half-time TAD-advisor. On the other hand, the lab scale (and sometimes pilot-scale) composite production facilities of the Composite Materials Group (prepreggers, autoclave, RTM and VARI, compression moulding presses) were not fully occupied. This inspired Ignaas Verpoest to propose to Herman Derache, director of Sirris, to develop the innovative concept of a 'composites application lab', a joint venture between KU Leuven and Sirris. KU Leuven (MTM and PMA, Prof. Dirk Vandepitte) would bring in the use of their composites processing equipment, whereas Sirris would provide personnel and the organisational framework.

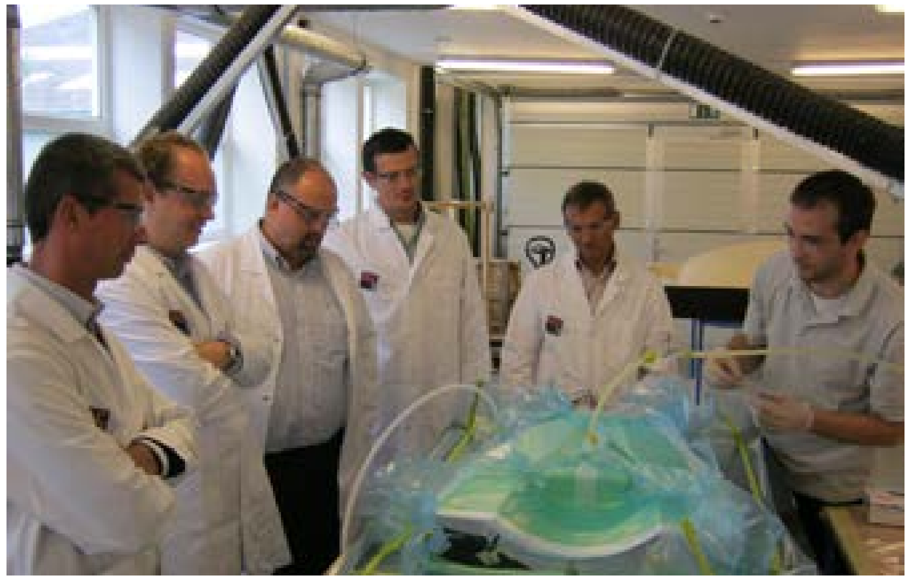
SLC, the Sirris-Leuven Composites Application Lab, was founded in 2009. The university further-more invested in the infrastructure, thanks to the strong support of vicerector Prof. Karen Maex, general manager Prof. Koenraad Debackere and LRD-director Paul Vandun. Bart Vangrimde, at that time at Sonaca, returned to Leuven to become the first director of SLC.

Now, in 2013, SLC has developed into an indispensable link in the value chain from university research to industrial reality in the value chain of composites in Flanders. A team of five engineers, managed by Markus Kaufmann, having their own lab facilities (RTM and compression moulding) combined with the composite processing facilities at KU Leuven and the composites knowhow at Ghent University (prof. Joris Degrieck, who joined in 2012), is carrying out applied research projects and short term consultancy on the demand of the local composites industry. The recent integration of the university colleges into KU Leuven, and with Jan Ivens recently joining the SLC Steering Committee, together with the reorganisation inside Sirris, intensifying the link with other Sirris labs, has further strengthened SLC.

Herman Derache and prof. Koenraad Debackere opening the new SLC-lab on 12th of May 2012, with SLC engineers Bart Waeyenberg and Linde Devriese holding the carbon fibre ribbon

An overview of the RTM- and VARI equipment at the SLC lab

SLC lab
Sirris Leuven-Gent Composites Application Lab



Bart Waeyenbergh during a training seminar at the SLC-lab

START OF THE NANO WORK

COLLABORATION WITH NANOCYL

In the second half of the decade, the group extended its research activities towards nano-engineered composites. The work with carbon nanotubes (CNTs) began in the academic year of 2007-2008 - quite late considering that CNTs were discovered in 1991 and some research groups were already active in this field in the late 90s. There were some reservations, and even resistance, to beginning nano-work in the Composite Materials Group at KU Leuven. This was mainly related to a poor understanding of how to benefit from nano-scale reinforcements in composites already reinforced with microscopic fibres. At that time, CNTs were well explored as a reinforcing component in polymers, but their integration in structural composites was still very limited.

The interest in the CNTs research was awakened when we were approached by Nanocyl, the Belgian company specializing in carbon nanotube technologies. Luca Mezzo, representing the research and development division at Nanocyl, wanted to expand the application of CNTs toward polymer composites and contacted us for expertise. This led to the establishment of a fruitful collaboration that still continues today. In the framework of this collaboration, the team in Leuven welcomed Nanocyl employee Dr. Ajay Godara who, together with Dr. Ashish Warrier (visiting postdoctoral fellow funded by FWO), investigated the processing and mechanical performance of composites reinforced with CNTs.

Larissa Gorbatikh

The Composite Materials Group welcomed Dr. Larissa Gorbatikh in 2007 after her relocation to Belgium from the United States of America where she was Assistant Professor at the University of Massachusetts Lowell and before that at the University of New Mexico. Her collaboration with the group, however, started three years earlier when Prof. Paul Van Houtte introduced her to Prof. Stepan Lomov. At that time she was interested in the toughening mechanisms of hierarchical materials and biological composites. Originally from St-Petersburg (Russia), she received training in Boston in the group of Mark Kachanov – one of the leading scientists in the field of micromechanics of materials and a former student of Jim R. Rice (known for the introduction of the J-integral). The current work on nano-engineered composites is, therefore, a combination of materials science and mechanics approaches inspired by naturally occurring composites.

FIRST SUCCESS

Among the first successful developments was an approach to deliver CNTs to the surface of fibres by dispersing them in the fibre sizing formulation. The advantage of this method was that it introduced no damage to the fibres in comparison, for example, with grafting of CNTs directly on fibres – an approach that was widely explored by other groups at that time. It also had clear scale-up perspectives from laboratory to industrial techniques. This approach was later patented by Nanocyl and KU Leuven. The results of microindentation tests on glass fibre/epoxy composites revealed a significant increase in interfacial shear strength when CNTs were present in the fibre sizing. The interface characterization was done in collaboration with Dr. Gerhard Kalinka from BAM (Bundesanstalt für Materialforschung und -prüfung) in Berlin.

In the same period, Dr. Larissa Gorbatikh joined KU Leuven and was given the opportunity to build a new research direction in the group out of this first success. From that point on, nano-engineered composites became one of the four strategic lines of research with its own challenges and scientific questions. Understanding of how to intelligently combine microscopic fibres and nanotubes for the toughness improvement has been one of the focal points of this research.

DEVELOPING CONCEPTS FOR NANO-ENGINEERED COMPOSITES

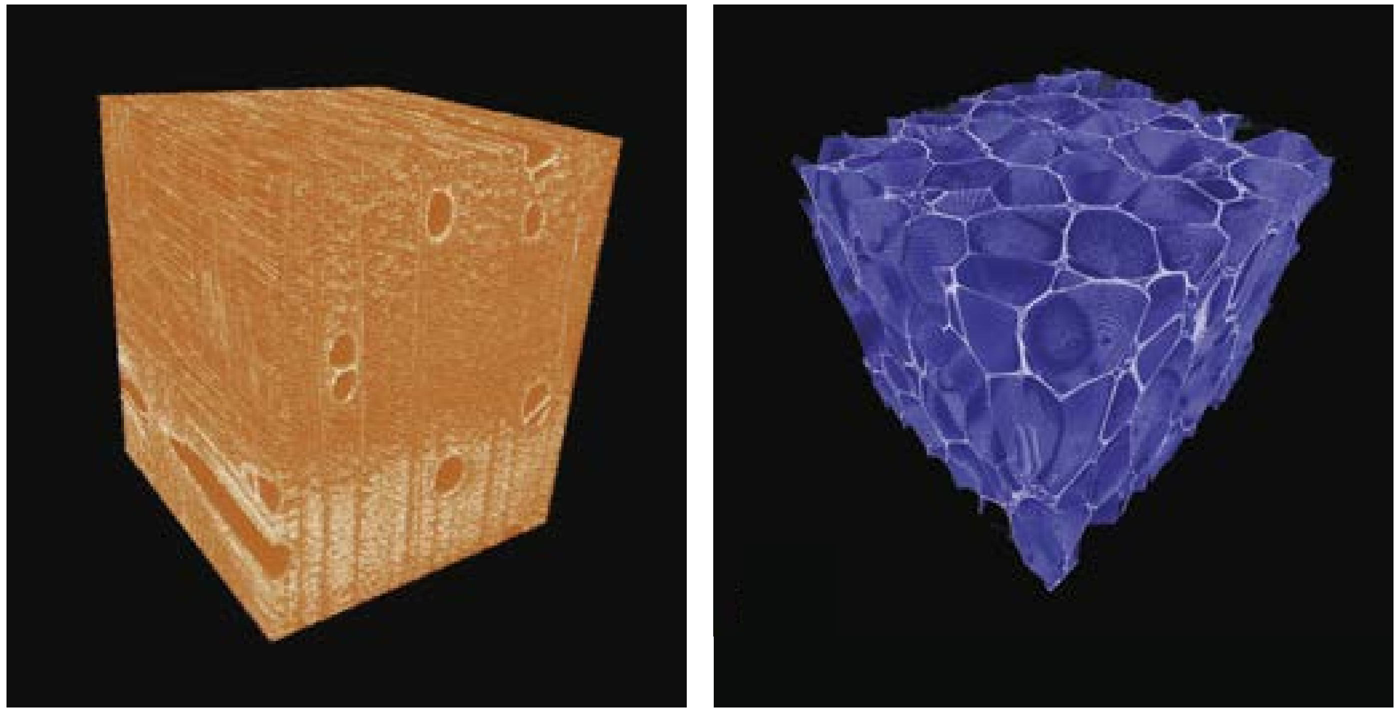
Encouraged by the first results with Nanocyl, everybody felt that the time had come to develop a better understanding of the fundamentals. At the same time, Dr. Larissa Gorbatikh produced some unexpected modelling results that indicated that nano-structured matrices could be used for redistribution of stress concentrations on the micro-scale. The group brought together a multi-disciplinary team of experts from KU Leuven: Prof. Maria Seo (carbon nanotube synthesis at MTM), Prof. Bart Goderis and Prof. Erik Nies (polymer chemistry and molecular modelling respectively both at the Chemistry Department). The team submitted a GOA project proposal for university funding, which was granted. Thanks to this funding opportunity Niels De Greef and MohammadAli Aravand started their PhD research on nano-engineered composites. They are currently exploring different strategies for controlled positioning of CNTs in the composites. In Niels' research, CNTs are grown on fibers using novel synthesis processes that do not introduce damage to the fibers. In Ali's thesis, CNTs are integrated in the polymer matrix with a phase separated morphology. Details about the work performed in this project are described in the next chapter.

NANO-REINFORCED FOAMS

In parallel with the research on nano-engineered composites, the group also started activities on nano-reinforced polymeric foams. This was made possible within the framework of the large scale European project, NANCORE. The Composite Materials Group was invited to join this project by KU Leuven colleague Prof. Paula Moldenaers from the Chemical Engineering Department. The goal of the project was to develop alternative core materials to balsa wood and PVC foams widely used in light-weight sandwich structures in wind energy and shipbuilding applications. Closed cell PP and PU foams reinforced with nanoclays and carbon nanotubes were identified as promising candidates. NANCORE helped to establish close collaboration with the group of Prof. Miguel Ángel Rodríguez-Pérez at the University of Valladolid. From working contacts with this group many interesting ideas were generated, including a concept on how to produce anisotropic foams, which had been proposed by Ignaas Verpoest as an alternative to the isotropic foams in bicycle helmets, in order to reduce the dangerous rotational acceleration of the brain; this will be further discussed in the next chapter of the book.

PhD researcher Oksana Shishkina has been investigating the structure-property relationship of balsa and polymeric foams using both experimental and modeling techniques. Important knowledge was acquired in the characterization of foam morphology using nano-computed tomography and foam deformation using a micro-compression device inside an SEM chamber. Additionally, a methodology was developed to characterize the fracture toughness properties of foams under mode-I and mode-II fractures, which are currently not standardized for foams. On the modeling side, a multi-scale model was developed to predict the elastic properties of foams that accounts for the presence of nanoclays and the bending deformation of cell walls.

Micro-computed tomography images of the microstructure of balsa and PVC foam.



COMPOSITES-ON-TOUR 1

The aim of the Composites-on-Tour initiative was to explain the mystery of composites, the very simple fact that combining rather weak plastics with simple glass or carbon fibres creates an extremely strong, stiff and light material.

How to convey this message to as large and as diverse an audience as possible, all over Europe? Being inexperienced in science communication can be an advantage: one can dream without being hindered by previous experiences. A mobile exhibition, explaining the mystery of composites, travelling through Europe might still be rather evident. But we also wanted the general public to discover how designers reacted to the potential and challenge of these new materials.

Finding an enthusiastic team to realise these ideas was not that difficult: composites scientists from the universities of Naples (Ignazio Crivelli-Visconti), Liverpool (Caroline Baillie), Delft (Adriaan Beukers), and of our own university in Leuven, teamed up with design specialists from VIZO (now Design Flanders, Johan Valcke and Ingrid Vandenhoudt) in Brussels and the Design Museum (Lieven Dhaenens, Monique Bucquoye) in Gent. The Belgian company, CompositTrailer created the world's first full composite trailer, the mobile house for our travelling exhibition, explaining the science behind composites.
It travelled 15.000 km through Europe, visiting 40 cities in 8 different countries, attracting more than 30.000 visitors in such diverse places as schools and highway gas stations, summer beaches and historic city centres, company canteens and science museums!

The enormous task of co-ordinating the creation, building and touring of the mobile exhibition was performed by two young scientists, Yves Vandewyagaert and Herman Lemmens, in close collaboration with Prof. Lut Pil from the Faculty of Arts at KU Leuven. Jo Mariën and his team of Technicians Kris Van de staey, Manu Adams, Bart Pelgrims and Johan Vanhulst, together with many PhD-students, spent weeks to built the exhibits and to help at the Composittrailer company to add special constructions to the trailer. Jo Emmers, the truck driver, being a circus artist, was the big animator of the mobile exhibition. More than 80 young composites researchers from 20 local universities guided visitors through the mobile exhibit, and enjoyed the challenge of explaining the subject of their research to non-specialists.

The second part of the Composites-on-Tour initiative, highlighting the relationship between composite materials and design, was realised through the International Composites Design Competition, organised by Design Flanders. The exhibition of the 12 selected designs in their gallery in the centre of Brussels was opened during the European Science Week, one day before the "From Bakelite to Composite" – exhibition in the Design Museum in Gent. The latter, more historical exhibition illustrated the use of composites in consumer goods, starting from Bakelite radios and progressing through history through Charles' Eames' first composite chair up to the current F1-racing cars. This exhibition attracted a record number of 25.000 visitors.

The whole project was financially supported by the European Commission in the framework of the European Science Week 2002 fund, and by some European composites companies.
One year later, in April 2003, we were surprised and proud that the JEC Group, specialised in the promotion of composites, and organizer of the world's largest composites trade show, the "JEC Composites Show" in Paris, selected Composites-on-Tour for a Special Award. It was Mrs. Frédérique Mutel, CEO of the JEC Group, who nominated Composites-on-Tour as a candidate for the Descartes Science Communication prizes, installed by the European Commission. On 2 December 2004, Ignaas Verpoest received, on behalf of all the Composites-on-Tour team members, the first Descartes Science Communication Award, from the hands of EU-commissioner Janez Potocnik.

Than, Surya and Ignaas finishing graphite models for the mobile exhibition, while the trailer is under construction at CompositTrailer

Frederik Desplentere (left) and Ignaas Verpoest (right) with three researchers from local universities during the Composites-on-Tour visit to Burgos.

The Composites-on-Tour exhibition in Antwerp

Children enjoying the 'closing the loop'-exhibit on biobased composites at a stop in Salamanca (Spain)

(top) Ignaas Verpoest receiving the Descartes Prize, from Janez Potocnik, EU Comissioner, and with sir Savid Attenborough, the other Descartes Prize winner in the back.
(middle) Ignaas Verpoest explaining composites to the general public at the opening in Brugge
(bottom) Global view of the exhibition 'From Bakelite to Composite' at the Design Museum in Gent

COMPOSITES-ON-TOUR 2

The second Composites-on-Tour initiative (2006-2007) was again financed by the European Commission as part of the 6th framework program. The positive experience during the first Composites-on-Tour inspired us to intensify the interaction between design and materials science: the scientific exhibition should now become an integral part of the design exhibition, and again travel around Europe.

The Composite Materials Group at KU Leuven coordinated the whole project together with Lut Pil (professor at the LUCA School of Arts, Gent). A group of PhD-students needed several brainstorming sessions to come up with attractive concepts for interactive exhibits, explaining what composites are, how they are produced and why they are so interesting. Eight mobile exhibits where then designed and realised by industrial designer Jan Hendrickx and the MTM technical team (Bart Pelgrims, Kris Vandestaey and many others), supervised by engineer Jo Mariën. They were first shown (February 2007) during a special exhibition "XTRA Strong/Light Composites" in the Arenberg library of KU Leuven, conceived by Ignaas Verpoest and Lut Pil, together with new designs from the winners of the first Composites-on-Tour design competition (Clem Van Himbeeck, Weyers&Borms) and an exclusive overview of the composite designs of the famous designer Ron Arad. Ron Arad was one of the 10 international jury members of the second design competition, coordinated by Design Flanders (Johan Valcke, Ingrid Vandenhoudt). The selected 22 designs Sébastien Dubois (Canada) and Poul Christiansen & Boris Berlin (Denmark) were displayed together with the scientific exhibition, first at the Gallery of Design Flanders in Brussels, and then in the galleries or exhibition rooms of the project partners (design organisations) in Barcelona, Budapest, Eindhoven, Ljubljana and Paris (both at the Cité des Sciences and in the JEC-show). An estimated number of 50.000 people have visited the exhibition, which was widely covered in national news media (newspapers, TV, radio).

In parallel with these exhibitions, 9 workshops on composites have been organised, attended by more than 400 designers from all over Europe.

Top: **Ignaas Verpoest explaining details on the composite bench to profs. Lazslo Kollar and Jozsef Karger-Kocsis of Budapest University of Technology and Economy**

Bottom & to the right: **Global view of the Composites Design Competition exhibition in Budapest**

Bart Pelgrims and Ignaas Verpoest with local workers building up the Composites-on-Tour exhibition at JEC 2007 in Paris

Composite designs by Ron Arad at the X-tra Strong/Light exhibition at the Arenberg Library in KU Leuven, February 2007

The scientific part of the Composites-on-Tour 2 travelling exhibition: (top) **Prof. Karel Van Acker and Aart van Vuure testing the impact tester,** (right)**The demo compression moulding machine**

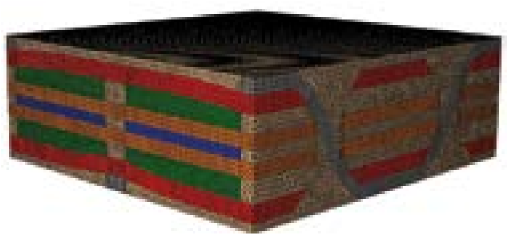
GOING **STRONG**

2010 - present

The current decade has started strong, with many new exciting projects and initiatives. Motivated to make structural composites tougher, the group has endeavored on the path of fibre hybridization, nano-modifications and engineering with novel ductile fibres. In the bio-composites team, a strong boost in flax and bamboo fibre composites research has been seen. The first few years have been marked with a steady increase in research on textile and random fibre composites, and developments of in-situ experimental techniques for the damage characterization. On the side of process and application development, there has been a lot of enthusiasm around design of new materials for the next generation Samsonite suitcases, bicycle helmets and smart furniture.

COMPOSITES ON THE MESO- AND MACRO-LEVEL

In the last years of the previous decade, the well-established research in textile composites in Leuven seemed to be endangered by "maturity" of the field: there was an impression that composites were moving away from science and research in academia toward development in industry. This was even reflected in the attitude of the funding bodies, especially on the national level. However, several factors worked against this tendency, defined, in large part, by the industrial demand from the aeronautic, automotive and wind energy sectors. As a result, in the new decade the Composite Materials Group is experiencing a steady increase in textile and random fibre reinforced composites research which is co-ordinated by Stepan Lomov.



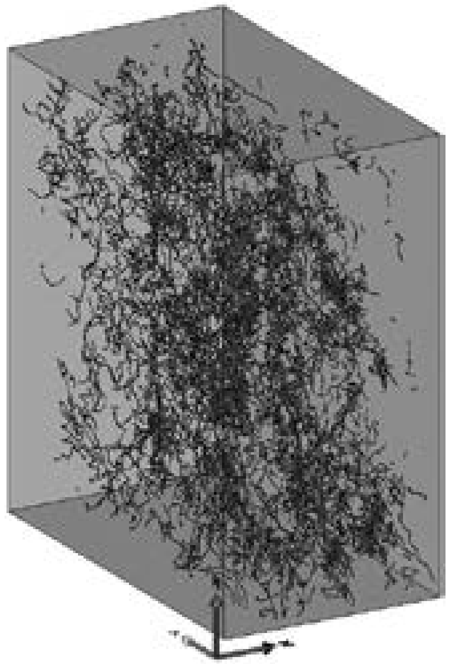
Finite element mesh of 3D woven composite

WISETEX AND FINITE ELEMENT TEXTILE COMPOSITE MODELLING

The interest in the WiseTex software suite still grows. There are four main demands which are drivers of this interest. These demands are answered by the software: firstly, fast micromechanics calculations (provided by the method of inclusions); secondly, permeability modelling; thirdly, the link to general purpose finite element packages; and finally, the use of the software in textile education. The WiseTex development strategy now puts the focus on creating links between the geometrical models of WiseTex itself and other elements of the integrated modelling of textile composites. On one hand, WiseTex can be considered as a post-processor for upstream models of textile production processes. On the other hand, WiseTex simulations of the internal textile geometry can be used as a pre-processor for downstream modelling of composite manufacturing (forming, impregnation) and composite performance.

The recent development of an open (XML) data format, in collaboration with TU Munich (Prof. Klaus Drechsler), has promoted the use of WiseTex in conjunction with custom user software tools. For example, in TU Munich, WiseTex is linked upstream to models of the braiding process and downstream to the structural analysis of composite beams and impregnation simulations. In the EU funded project SIMPOSIUM, Stepan Lomov, in collaboration with the Centre Ènergie Atomique (France), is developing a software "connector" of WiseTex to CIVA, a widely used software for ultrasonic non-destructive testing. In another EU project, QUICOM, PhD researcher Ilya Straumit works on the direct input of textile internal geometry (measured by µCT) to WiseTex and/or meso-FE models.

The transformation of the WiseTex models into finite element meshes is of high demand by both industrial and academic WiseTex users. The Composite Materials Group continues collaboration with Dr Dmitry Ivanov (now at the University of Bristol) on developing automated tools for this transformation. Continuing the earlier work of Dr. Sergey Ivanov, a visiting researcher, Enrico Bedogni (University of Parma), has developed quality FE models for 3D fabrics. In Leuven, PhD researcher Seyedahmad Tabatabaei studies the capabilities of superimposed meshes, introduced earlier in the M3 method of Prof. Masaru Zako and Prof. Tetsusei Kurashiki in Osaka University (who spent his sabbatical in Leuven in 2010). The ultimate aim of this work is to create a "press button" solution for transformation of a WiseTex geometrical model into a quality FE mesh, preserving the versatility of WiseTex and without using *ad hoc* "tricks" for particular structures.



Random steel fibre composite, microCT image

Fatigue finite element modelling is continuing in collaboration with Prof. Joris Degrieck and Prof. Wim Van Paepegem from Ghent University and Prof. Satoshi Hanaki of Hyogo University.
Permeability modelling in FlowTex has been recently enhanced by Dr Bart Verleye and his master student Jonas De Greef (Department of Computer Science, KU Leuven). An impressive increase of the algorithm's effectiveness opens new possibilities for multi-scale integration of WiseTex software.

RANDOM FIBRE COMPOSITES AND METHOD OF INCLUSIONS

Random fibre composites are a natural field for employing the method of inclusions. This topic, which is of paramount interest to the automotive industry, is being intensively researched in the PhDs of Yasmine Abdin and Atul Jain, thanks to a strategic collaboration with LMS International, a large spin-off company from KU Leuven. This work is supported with national funding via the Baekelant program of IWT and the SIM program Nanoforce, and is carried out in close collaboration with Prof. Joris Degrieck and Prof. Wim Van Paepegem of Ghent University. The ultimate aim of this work is the creation of validated fatigue micromechanical models of random fibre composites, integrated with the LMS software for static and fatigue structural analysis (Christophe Liefooghe).

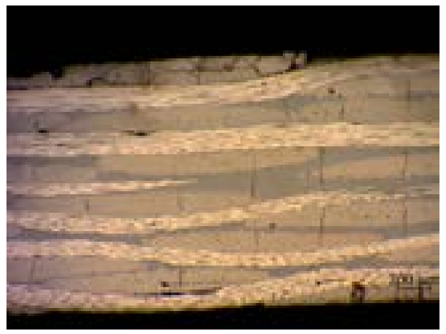
The scientific challenge that is faced is the advancement of stiffness predictions towards damage, debonding, strength and further fatigue. A specific challenge is encountered in the modelling of steel fibre random composites: the extremely fine and flexible fibres are wavy. The transformation of the wavy fibre into a set of mechanically equivalent inclusions links the current research with models of the previous decade: the structure of non-woven materials and using inclusion models to model crimped yarns in textile composites. The theoretical foundations of the method of inclusions are studied intensively, with major conclusions on the adequacy of different variants of homogenisation schemes and benchmarking against finite element modelling.

NEW EXPERIMENTAL TECHNIQUES

Experimental methods for measuring textile deformability have been further developed by Dr Dmitry Ivanov, Dr Kristof Vanclooster and visiting researchers Dr Marcin Barburski (Lodz Technical University, Poland) and Dr Virginia Sacevičienė (Kaunas University, Lithuania). The European project INFUCOMP and the collaboration with Bekintex on steel fibre knits serve as a framework for these developments. The KU Leuven lab now has the capability to perform full characterisations of textile reinforcements for forming simulations, including testing at the process temperature of preimpregnated thermoplastic plies and self-reinforced thermoplastics (PhD research of Yentl Swolfs).

The Department MTM, via Hercules funding of the Flemish Government, has built a state-of-the-art micro-computed tomography lab (Prof. Martine Wevers), which allows for the detailed investigation of the textile composite internal architecture. PhD researcher Ilya Straumit

Test setup for studies of textile reinforcement draping with mould at the top and DIC-cameras at the bottom left



Damage in a woven carbon fibre composite

works on the transformation of µCT images into geometrical and finite element models, and on the further assessment of the composite mechanical properties. Visiting PhD researchers Galina Harjkova (from TU Riga), together with Marcin Barburski, and Juan Pazmino (Politechnico di Milano) applied µCT to various textile materials. Andy Vanaerschot, a PhD researcher jointly supervised with Prof. Dirk Vandepitte, builds his variability models based on µCT information.

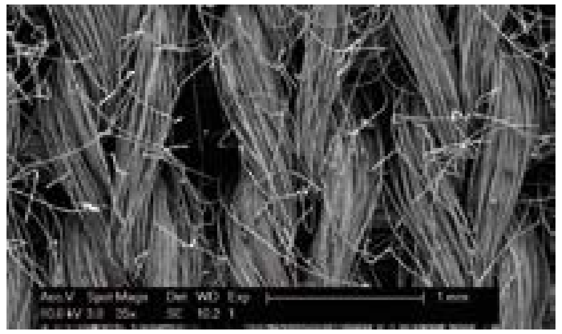
Experimental methods for damage characterisation are being further advanced by Dr Larissa Gorbatikh and Dr Sergey Ivanov, who have introduced microscopy techniques as well as enhanced acoustic emission and optical damage monitoring within the framework of M-RECT and IMS&CPS EU-funded projects and a number of Master theses. Being connected to nano-related research (see the next section), these developments are of an utmost importance for precise damage characterisation of textile composites. Important innovations in damage characterisation that have been realised include the frequency analysis of acoustic emission events and a detailed quantitative characterisation of crack density in textile composites. µCT characterisation of damage is an emerging experimental approach with challenging issues of small specimen size, image resolution and processing of the image into quantitative damage parameters. Visiting PhD researcher Malika Kersani (University of Algeria) applies these advanced damage characterisation methods to flax fibre composites.

Dr Katleen Vallons continues applied studies on the fatigue behaviour of composite materials, investigating various phenomena of both carbon and glass reinforced materials under fatigue loading. Her work on glass unidirectional non-crimp fabric composites for wind mill blades applications (in an industrial project with Owens Corning) explored how the fatigue behaviour depends on the parameters of the reinforcement textile manufacturing. In the framework of the Toray Chair for composites, a specific study was started in order to characterise the fatigue properties of a novel type of carbon fibre prepreg from Toray. Stepan Lomov continues exploring the links between damage development in quasi-static testing and fatigue limit. New international collaborations are emerging and old are strengthening in the fatigue field, particularly with Prof. Valter Carvelli (Politecnico di Milano), Prof. Janis Varna (Lulea University, Sweden) and Prof. Ramesh Talreja (Texas A&M University).

VARIABILITY AND STOCHASTICITY

The variability and stochastic characterisation of composite mechanical properties have come more and more to the forefront of industrial interest. PhD researchers Valentin Romanov and Yentl Swolfs have developed new approaches in the old problems of the random placement of fibres in unidirectional composites and of unidirectional bundle strength (referred to in more detail in the next section). The PhD work of Andy Vanaerschot (co-supervised by Prof. Dirk Vandepitte, Department of Mechanical Engineering), also on the subject, benefits from a strong collaboration with Dr Brian Cox (Teledyne, California). The strength of this work is based on the use of precise µCT measurements of the actual tow geometry in textile composites, and well-founded mathematical algorithms for the description of correlations in the tow path variability based on a Markov chain approach. The correlated nature of the textile material stochasticity was first addressed in the PhD of Frederik Desplentere in the previous decade. It is revisited now on a new level. Variability of the reinforcement internal structure is studied by Mireya Olave, in a joint PhD research between KU Leuven and Ikerlan (Mondragon, Spain), supervised by Stepan Lomov, Dirk Vandepitte and Laurentzi Aretxabatela.

The research into reinforcement variability is more and more of interest to industry, especially for aeronautic applications. Understanding of the stochasticity, which is inherent to fibrous reinforcements, allows the introduction of scientifically sound safety coefficients for composite materials. Apart from textile reinforcement, non-conventional laminates (tape laying and other robotic lay-up techniques) were investigated in the previous decade by Dr Larissa Gorbatikh (AUTOW European project) and will continue in the CANAL European project starting 2013.

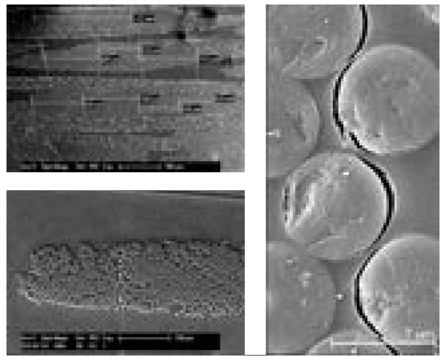


Steel fibre knitted fabric used in the forming studies of Marcin Barburski

STEEL FIBRES

Extremely thin (5-30 µm) steel fibres, produced by Bekaert, are a promising reinforcement for tough composites: steel combines the stiffness of carbon fibres with a ductility which is (at least) five times greater. Funded by the Flemish Government via the Strategic Initiative Materials (SIM), steel reinforced composites are studied by PhD researchers Michael Callens (long fibre composites with steel textile reinforcements) and Yasmine Abdin (random steel fibre composites). The work on composites reinforced by steel fibres is addressed in detail in the section below.
In addition to composite applications, the steel fibre textiles are also used as a mould surface material in automotive glass production. The quality of the knitted mould coverage for glass forming was always assessed qualitatively, by inspection, and the draping procedures were defined by the workmen's skills. The introduction of an instrumented, automatic measurement of the glass optical quality urged the industry to seek better control over all the production preparation steps and quality of the textile coverage. In collaborative research with Bekintex, Dr Kristof Vanclooster and Dr Marcin Barburski extended the experimental techniques, developed for composite reinforcements, to the characterisation of knitted steel fabrics for glass forming. The objective mechanical testing of the fabric, developed in the Composite Materials Group work can be seen as an expansion onto the new field of an old approach of Objective Textile Evaluation, elaborated in 1970s for garment industry by S. Kawabata.This work is a perfect example of multi-disciplinary research on one hand, and the mutual interest of common themes in textile and composites material science, on the other. Glass forming processes have nothing to do with composites production – nevertheless, the same "draping on a mould" step is present, which allows efficient cross-fertilisation of the studies in the two application fields.

COMPOSITES ON THE MICRO- AND NANO-LEVEL



Damage in the form of matrix cracks in fibre-reinforced composites

QUEST FOR TOUGHER COMPOSITES

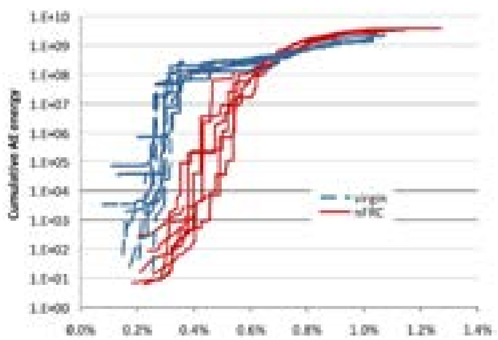
The work performed in the Composite Materials Group is focused at overcoming two major limitations of fibre-reinforced polymer composites. The first one is their low strain-to-failure (of only a few percent), which is a direct consequence of the intrinsic brittleness of reinforcing fibres. The second one is the rather low strain threshold for the onset of damage in the form of matrix cracks, often starting at interfaces. The challenge is, however, that traditional approaches to improving the toughness of composites by increasing the toughness of the matrix and tuning the properties of the fibre/matrix interface are about to exhaust their potential. Important breakthroughs in this area are envisioned with the help of novel toughening mechanisms and new combinations of materials.

In recent years, the team has been exploring different strategies to toughen structural composites. These strategies include nano-engineering, fibre hybridization, using ductile structural fibres and mimicking naturally occurring composites.

NANO-ENGINEERED COMPOSITES

The next level of toughness improvement in composites is envisioned with the help of modifications on the nano-scale. Composites, which simultaneously combine nano-scale and micro-scale reinforcements, are frequently referred to as nano-engineered fibre-reinforced composites. In the Composite Materials Group, we mainly work with carbon nanotubes (CNTs). CNTs are integrated in a composite either by mixing them in the polymer matrix, adding them in the fibre sizing or growing them on fibres.

Up until now, the team working with Dr. Larissa Gorbatikh has shown that the presence of CNTs in a composite strengthens the fibre/matrix interface, suppresses the formation of matrix cracks, hinders the onset and propagation of delaminations, and extends the fatigue life of the composite. Many of the early studies on the topic were done in the framework of master theses (Niels De Greef, Yao Ding, Taotao Li, Thijs Clarkson, Dries Beyens, Nakul Prasad, Alexander Haesch). In the last few years, this research focus has also been supported by external funding from the European Commission (projects like IMS&CPS and M-RECT).

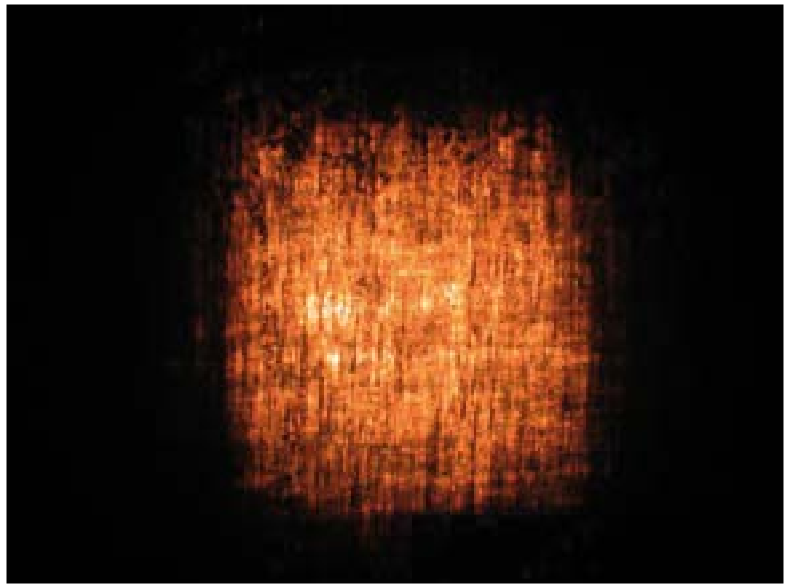


The shift of the cumulative acoustic emission curves to higher strains in the nano-engineered composite indicating a hindering effect of carbon nanotubes on the onset and development of matrix cracks.

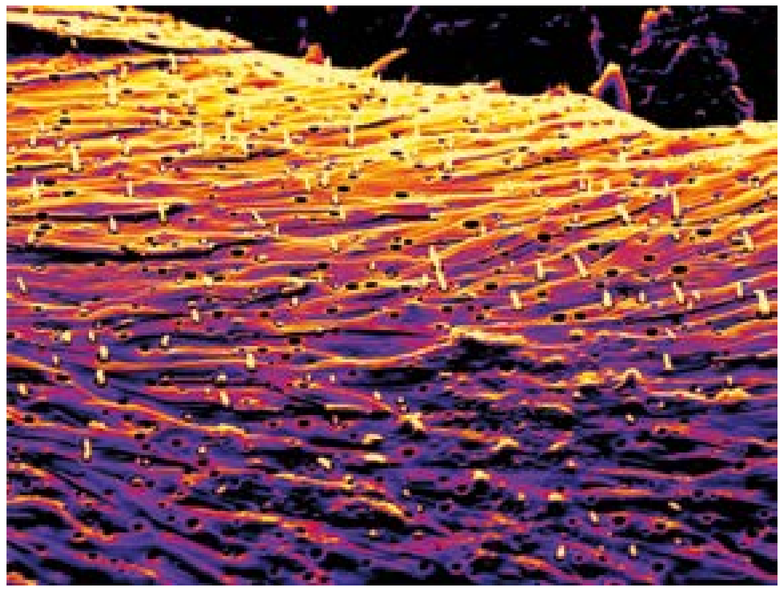
CHALLENGES WITH THE CNT DISPERSION

CNTs are prone to form agglomerates, which are then likely to generate stress concentrations and lead to a poor mechanical performance of the resin. This explains why the characterization of CNT dispersion quality, and understanding how CNTs agglomerate, are important research topics in the group. The state of the CNT dispersion in a composite depends not only on the original quality of the dispersion in a masterbatch, but also on the effects of time, thermal history, pressures and the processing parameters used to make this composite.

PhD researcher MohammadAli Aravand developed a methodology to characterise the evolution of the CNT dispersion state at different stages of composite preparation. In collaboration with Dr. Nadir Kchit from Nanocyl, we are also trying to understand aging of the CNT dispersion in commercially available masterbatches. When nano-reinforced polymers are used for production of structural composites, yet another consideration is important, namely how the dispersion of CNTs affects their final position in the composite. This is particularly relevant for composites with textile reinforcement, where the distribution of fibres is highly non-uniform.



A backlight microscopy image of a woven glass fibre/epoxy composite reinforced with carbon nanotubes indicating non-homogeneous distribution of CNTs on the level of a single yarn. Due to a formed CNT network, nanotubes tend to localize in resin rich pockets around a fibre bundle *(The width of the image is about 8 mm)*



Fracture surface of a multi-phase epoxy/POM resin indicating high deformation of POM particles

MATRIX MORPHOLOGIES WITH HIERARCHICAL STRUCTURES

How to create matrix morphologies with hierarchical structures, and how to tailor them to achieve specific toughness properties in composites form yet another field of interest. At the moment, this is done by developing and investigating phase-separated epoxy/thermoplastic/CNT blends and their composites. In collaboration with Dr. Magali Coulard and Carmen Tola from Nanocyl, the morphology and interlaminar fracture toughness of carbon fibre composites based on multi-phase epoxy/PES matrices with carbon nanotubes were investigated. MohammadAli Aravand is studying how the phase separation in such blends is affected by the presence of CNTs. The effect of the compounding order of CNTs on the morphology and fracture toughness of such nanocomposites is also of interest. In some cases, CNTs mixed in one phase tend to migrate into the other phase. Preliminary studies indicate that this may have a significant effect on the mechanical performance of the materials.

PROCESSING OF NANO-ENGINEERED COMPOSITES

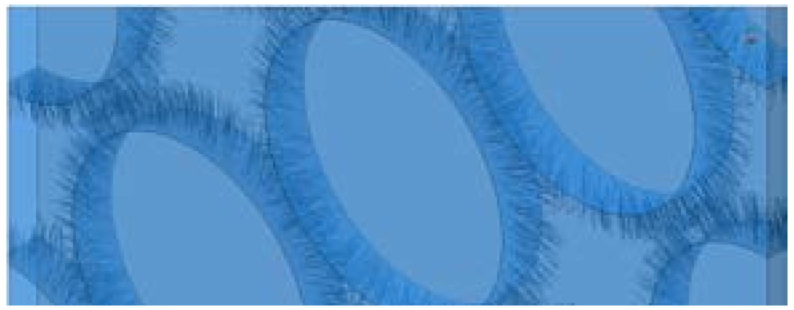
Processing of nano-engineerd composites can be done with conventional, well established technologies (prepregging, RTM, VARI, etc), but the processing conditions of some of them may require adaptation. For example, when CNTs are grown on fibres, the compressibility of the fibre bundles and fabrics decreases significantly. Thus, higher pressures are required to achieve the desired fibre volume fraction in a composite made of these CNT-grafted fibres. The compressibility of the CNT assemblies in composite materials is extensively studied by Stepan Lomov using both experimental and modelling techniques. The models that have been developed are able to predict the compression resistance of random assemblies of CNTs, CNT-grafted fibre bundles and fabrics. Different CNT assemblies have been experimentally characterised for the compression resistance. They came to us from our collaborators at Nanocyl (Matthieu Houlle), University of Twente (Zˇeljko Kotanjac, Vitaly Koissin), Massachusetts Institute of Technology (Brian Wardle and Sunny Wicks) and Cambridge University (Fiona Smail and Alan Windle).

MODELING OF NANO-ENGINEERED COMPOSITES

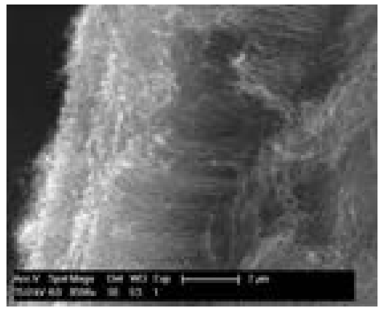
The dimensions of nano-reinforcements are immensely different from the ones we are used to in composite materials. For example, diameters of conventional fibres typically range from 5 to 20 µm whereas those of carbon nanotubes range from 1 to 100 nm. The use of nano-scale and micro-scale reinforcements in a single composite raises a series of fundamental questions about interactions between the microstructure and the nanostructure, and how to tune these interactions to control failure processes in the composite. Modelling approaches are expected to play an important role in addressing these questions. They will help to optimise the multi-scale structure of the composite and to reduce the large number of parameters that must be investigated experimentally.

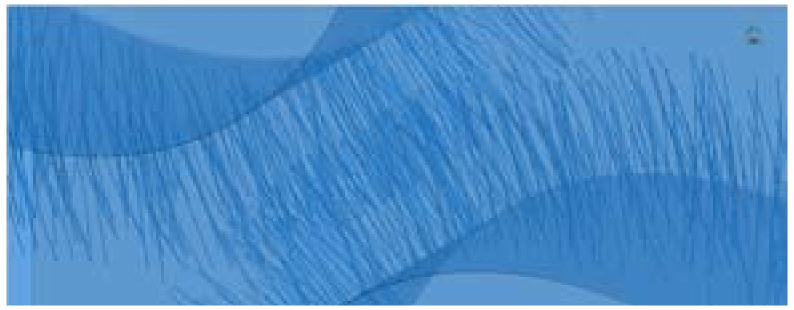
Three-dimensional models that simultaneously combine micro-scale and nano-scale reinforcements are virtually non-existent. Even for a two-

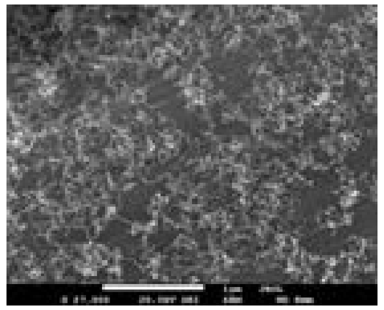
Carbon nanotubes grown on carbon fibres, as represented by novel models.



Carbon nanotubes grown on fibres





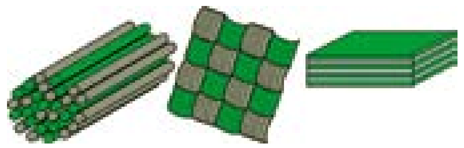


dimensional formulation, the availability of such models is very limited. In the framework of the European IMS&CPS project, Valentin Romanov developed a new model of nano-engineered composites where both fibres and nanotubes are considered in a single simulation. Any intermediate homogenization of properties or transfer of parameters from one scale to another is avoided. The model in this formulation was inspired by the interdependent nano- and microstructures of the naturally occurring composites studied by Larissa Gorbatikh.

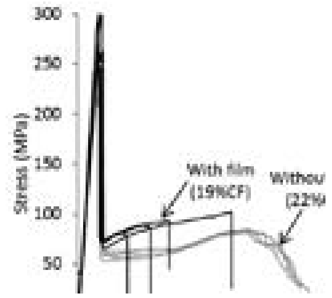
The model is currently being applied to investigate the effect of CNTs on the stress distribution in fibre reinforced composites in the cases when the CNTs are grown on fibres or added in the matrix. The developed approach to modelling of fibre-reinforced composites with carbon nanotubes is a promising tool to guide future developments in the field of nano-engineered composites.

HYBRIDIZATION WITH SELF-REINFORCED POLYMERS

Fibre hybridization is another approach to toughen composites that is currently being explored in the Composite Materials Group. Hybridization of two types of brittle fibres is well known from the work done in the 80s. It



Three hybridization strategies for combining brittle and ductile fibres: intrayarn, intralayer and interlayer



Stress-strain curves of hybrid carbon fibre/SRPP composites, showing the potential of increasing (total) failure strain of these composites

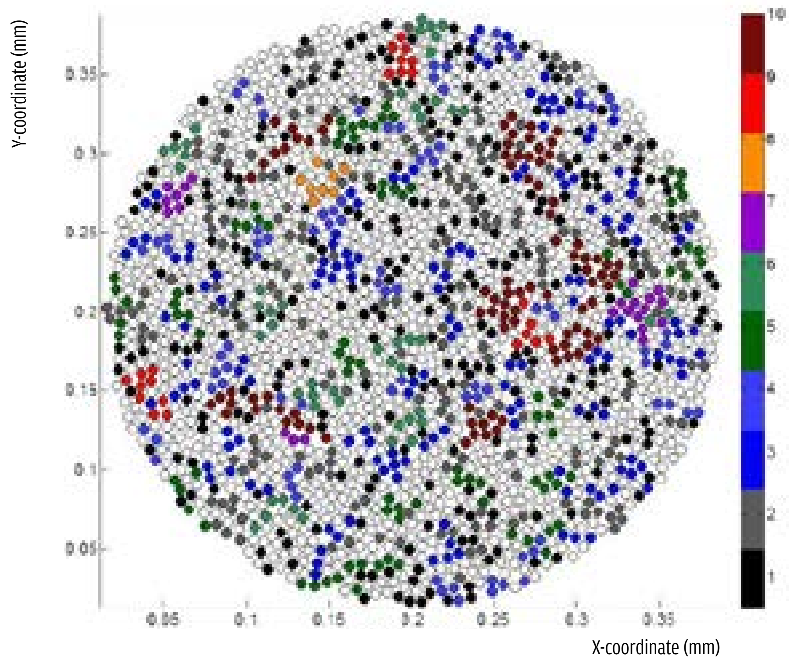
was mainly applied to carbon fibre composites, but due to the brittle nature of the hybridization fibre (usually glass or aramid with failure strains 3-4%), the toughness improvement achieved by this approach was moderate. Currently at KU Leuven, hybridization is performed with fibres that possess a strain to failure as high as 20%. Doctoral researcher Yentl Swolfs is investigating the hybridization of carbon fibres and ductile PP fibres. In the doctoral study of Michaël Callens, brittle fibres are hybridized with ductile steel fibres. The ductile fibres are tougher and thus have more intrinsic potential to absorb the energy released when the brittle fibre breaks. The ultimate goal is to tune microstructural parameters of the composite such that a catastrophic failure process is replaced by a more gradual one. This way, a significantly higher strain-to-failure, and thus better impact behaviour, can be achieved.

In the framework of the European project HIVOCOMP, different hybridization structures (interlayer, intralayer and intrayarn) are explored for composites made of carbon fibres and self-reinforced polymers. The studies rely on both experimental and modelling efforts. Other types of fibres including glass and steel are also being investigated. The research on hybrids with self-reinforced polymers began with the work of Marie Currie fellows Jon Ustarroz and Bettina Fabich as part of the EU MOMENTUM project. These preliminary studies were then further extended in the PhD dissertation of Ichiro Taketa, and are now being continued by Yentl Swolfs.

FAILURE MECHANISMS AND STRENGTH MODELS

A fundamental understanding of the failure of fibre-reinforced composites is important for the improvement of their overall performance. In the Composite Materials Group, the failure process in unidirectional fibre-reinforced composites was studied by Ichiro Taketa, a Japanese researcher who was sent to Leuven by his company, Toray, to carry out a PhD-study on carbon fibre composites. The focus of the thesis was on the tensile behaviour of unidirectional thermoplastic laminates. Global mechanical properties (such as 0° and 90° tensile strength), and microscopic mechanical properties (such as the work of adhesion, matrix modulus, matrix residual stress, interfacial shear strength, and interlaminar fracture toughness in mode II) were experimentally evaluated. Constitutive models, which describe the failure mechanisms of unidirectional laminates, were constructed using existing techniques, and the contributions of fibre and matrix/interface related parameters were clarified.

Currently, PhD researcher Yentl Swolfs is developing a new strength model for unidirectional composites. In this model, stress redistributions after a single fibre breakage, in both random and ordered fibre packing arrangements are first calculated using the finite element method. The stress fields obtained are then incorporated into a separate strength model, which is able to track the cluster development. This model is the first strength model for realistic random fibre packings. It proved that random fibre packings yield a small, but statistically significant difference in composite failure strain compared to regular packings. Future work will focus on extending this model to hybrid composites to predict their complex tensile behaviour.



Visualization of clusters of broken fibres in a unidirection composite loaded in the fibre direction. Colours correspond to clusters with different numbers of broken fibres

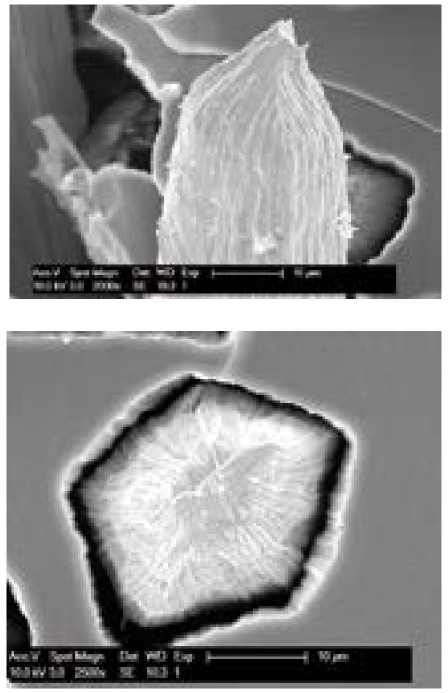
DUCTILE STEEL FIBRE COMPOSITES

Due to the intrinsic brittleness of high-performance fibres, traditional structural fibre-reinforced composites have limited ductility and toughness. The composite ductility can therefore be enhanced by choosing fibres that have a higher strain-to-failure. The choice of ductile fibres for the use in composites is currently limited to either polymeric fibres or natural fibres like silk. The high toughness of these fibres, however, comes at the expense of the low stiffness, which limits their use in structural applications.

Recently, a new class of ductile, yet stiff fibres became available for application in structural composites: annealed stainless steel fibres, which exhibit both high stiffness *and* high strain-to-failure. The stiffness of such a fibre is almost as high as that of carbon fibre (approximately 193 GPa), and the strain-to-failure is as high as that of silk fibre (up to 20%). In the framework of the Nanoforce project, funded by the Flemish government as part of the SIM-program, the Composite Materials Group, in collaboration with other partners, explores the use of these steel fibres as continuous reinforcement in polymer composites.

Ignaas Verpoest, who achieved his PhD-research on steel wires in collaboration with the Belgian company Bekaert, had already suggested to the Bekaert R&D-management in the 90s to consider the use of their unique steel fibres (with diameters down to 8µm) as reinforcement for composites due to their potential to combine high stiffness with high failure strain. Initial exploratory research however was performed on fine steel wires and on steel cords (as used in tires), with high strength and lower ductility, in the framework of an IWT-project. Later on, based on this project, Bekaert developed some interesting applications for such composites, like reinforcements for car bumper beams.

The focus on annealed, and hence ductile, stainless steel fibres of low diameters started in 2008 after Angela Durie from Bekaert and Aart van Vuure did some exploratory work. This resulted in a second IWT project



SEM image of a steel fibre in a fractured composite emphasizing fibre's irregular cross-section and plastic deformation

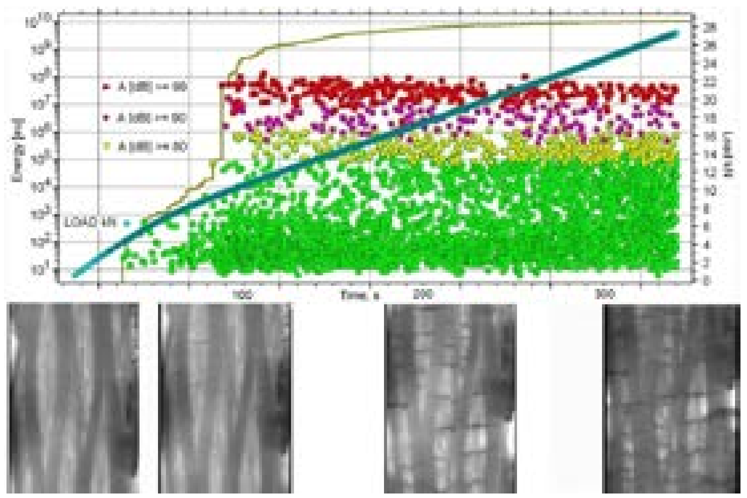
with Bekaert (Sophie Vandewalle) in 2010. Doctoral researcher Yasmine Mosleh has shown that steel fibre composites and their hybrids are excellent for energy absorption in impact. These initial results were sufficiently promising to start a more fundamental research project, in the framework of the NanoForce program of SIM, and in collaboration with several Flemish universities and research institutes. Doctoral researcher Michaël Callens is currently investigating different types of steel fibre quasi-unidirectional preforms, combined with different polymers and with different fibre surface treatments. The wet chemistry surface treatments are done in collaboration with colleagues from the Chemistry Department at KU Leuven – Professors Bart Goderis and Mario Smet and doctoral researcher Ellen Bertels, whereas the plasma treatments are carried out at VITO. Initial results indicate that high stiffness, yet ductile composites can be realised.

In the framework of the Nanoforce project, we also plan to develop strong and ductile composites based on novel fibers – aligned carbon nanotubes bundles – that are currently being produced in the group of Prof. Seo.

NANO-REINFORCED GRADIENTS IN STEEL FIBRE COMPOSITES

The work on steel fibre polymer composites raises a series of challenges. One of them is related to the high mismatch of properties between the steel fibre and the polymer matrix. Because steel fibres are very stiff and isotropic, they generate high stress concentrations at the fibre/matrix interface. These high stress concentrations can lead to an early onset of matrix cracks and reduce the ductility of the composite. In the framework of the doctoral studies of Michaël Callens, three strategies are explored to address this issue: to increase the interface adhesion strength, to increase the matrix toughness, and to stiffen the area around steel fibres. The grafting of carbon nanotubes (CNTs) on the surface of fibres is a promising approach to improve the properties of fibre-reinforced composites. In collaboration with FWO doctoral grantee Niels De Greef and Professor Maria Seo, CNTs are being grown on the steel fibre surface, and the grafted fibres are used to produce composites. The experimental work is supported by the modeling efforts of Svetlana Orlova and Baris Sabuncuoglu who examine the effect of the nano-built gradients around fibres on stress concentrations in the steel fibre composites.

Damage development in glass fibre composite as captured by acoustic emission registration and direct camera observations of cracks on the surface



UNDERSTANDING COMPOSITE FAILURE

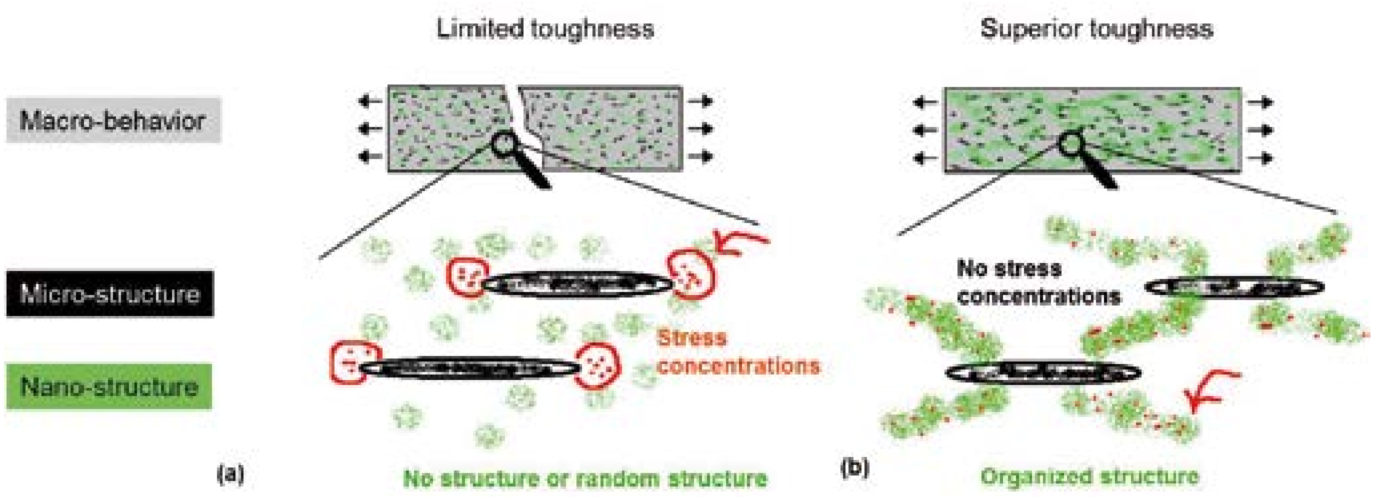
Improving the damage resistance of existing composites, or developing new ones with increased toughness, goes hand in hand with understanding how composites fail. Damage development is extremely complex in these high-performance materials. Failure processes unravel at different length scales and are intimately linked to the material's internal structure. They are dictated by the geometry of the reinforcement architecture on the meso-level, by the arrangement of fibres inside yarns on the micro-level, and by the polymer morphology and fibre-polymer interface on the nano-level. A significant effort in the group is put towards in-situ characterization of damage development on the meso- and micro-levels. In the framework of the European project M-RECT, Dr. Sergey Ivanov is developing a methodology for the in-situ characterization of matrix cracks in carbon and glass fibre composites under tensile loads. In the framework of the GOA project funded by KU Leuven, doctoral researchers MohammadAli Aravand and Michaël Callens are investigating ways to measure strains on the micro-level using digital image correlation techniques.

LEARNING FROM NATURALLY OCCURRING COMPOSITES

In the Composite Materials Group, we are keen to understand how nano- and microstructures interact, and how to manipulate these interactions to improve composite toughness. Many of our ideas for nano-engineered composites are inspired by naturally occurring composites. It is well recognized that nature uses more advanced principles to design materials for damage resistance than we do today.

The unique combination of strength and ductility in naturally occurring composites is attributed to their sophisticated structural organization. In the modeling work of Larissa Gorbatikh it was found that different mechanisms of failure initiation exist in a material with multiple levels of structural organization. A material can be made insensitive to the presence of micro-scale stress concentrators (inclusions, cavities, defects etc) by introducing a nano-reinforced matrix around them that forms a structured network.

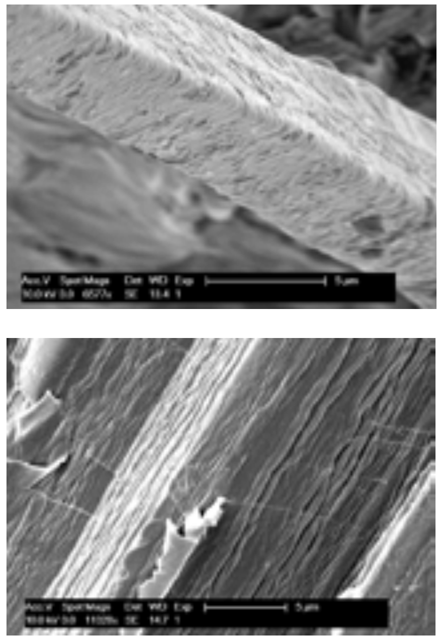
Two model materials with distinctly different mechanisms of failure initiation on the micro-scale: (a) stress concentration driven and localized (leading to limited toughness) and (b) stress concentration insensitive and distributed (leading to superior toughness). The difference in the failure initiation mechanisms is attributed to the difference in the nano structure of these materials: material in (b) has an intelligently organized nano-structure that connects microscopic inhomogeneities (inclusions, defects, etc) in a network.



RESEARCH ON BIO-COMPOSITES

At the beginning of the 4th decade of the CMG, the bio-composites team has shown strong growth and the group now counts 3 post-doctoral researchers and 7 PhD students (of which 3 should finalise their PhDs in 2013). Research has rolled over smoothly from the 3rd decade. The research on flax fibre composites has seen a strong boost, particularly because of the participation in the European Biobuild project and the involvement in CELC, the European Flax and Hemp Confederation.

BAMBOO FIBRE COMPOSITES



Microstructure of elementary bamboo fibres (Guadua Angustifolia); most elementary fibres have a double walled structure: a) primary, outer wall with 90° nanofibril orientation; b) secondary, inner wall with 0° nanofibril orientation

With Lina Osorio and Eduardo Trujillo approaching the end of their PhDs (funded by BelSPO Vietnam), having developed a novel method of long bamboo fibre extraction, the emphasis in the research is now shifting to exploitation of the long bamboo fibre technology. Lina and Eduardo won a prize from KU Leuven Research and Development for a business plan they wrote during a course about entrepreneurship. A so called 'Cantilever' project was obtained from the KU Leuven Industrial Research Fund, to develop the last phase in the development of a bamboo fibre prepreg tape. Three Master's students from Université Catholique de Louvain have helped to write a more detailed draft of a business plan for a possible spin-off company, for which they also won a prize from the BSE Academy in Brussels.

In the meantime, Lina and Eduardo have been finalizing their theses. Lina has focused on a detailed study of the microstructure of bamboo fibres and has linked the mechanical performance of the technical fibres to the microstructure and the properties of the elementary fibres. Eduardo has worked on various methods to measure and analyse the mechanical performance of the fibres and bundles of fibres (for instance, using Weibull statistics of strength). He has also studied the problem of overlapping the discontinuous fibres in a continuous tape, defining minimum overlap criteria and has also studied the thermal properties of the bamboo fibre composites.

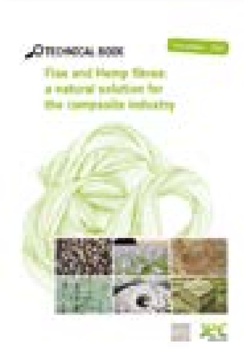
INTERFACES IN NATURAL FIBRE COMPOSITES

With the PhD of Ngoc Tran Le Quan finished and Carlos Fuentes almost finalizing his thesis, the physical-chemical-micromechanical approach to study interfaces in composites has reached a mature stage. By studying both the mechanical strength of interfaces, as well as the chemistry and physical-chemistry (surface energy components) of the fibre and matrix surfaces, it is possible to make a much more substantiated choice in fibre treatments or matrix modifications to control and optimise the interface strength and wetting (impregnation) characteristics. In this way, interface optimization becomes much less a matter of trial and error. Ngoc is now as a postdoctoral researcher selecting high performance thermoplastics in a collaborative project with natural fibre pioneers BComp from Switzerland. Collaborations to investigate interfaces outside of natural fibres are also explored.

GLUTEN BIO-POLYMERS AND COMPOSITES

In 2011, a second project on gluten biopolymers, a SBO (Strategic Basic Research) project sponsored by IWT, was started. Various new material concepts are being explored, such as thermoplastic vulcanizates and gluten fibres. The role of the Composite Materials Group is to explore the application of gluten in natural fibre composite materials. As a final result of this project it is envisioned to initiate some spin-off business activity. The research in the combined IOF Platform (see previous decade) and SBO projects has led to gluten formulations modified with small thiol containing molecules which show an improvement in strength, and a strain-to-failure of 50%, thus approaching the properties of epoxy resin. Nhan Vo Hong has, in his studies on natural fibre composites, made strong progress in the processing of the gluten materials. He has also made variants with only the gliadin fraction, better facilitating fibre impregnation. Both gluten and gliadin show decent adhesion to flax and bamboo fibres, but further work is being conducted to improve the interfacial compatibility.

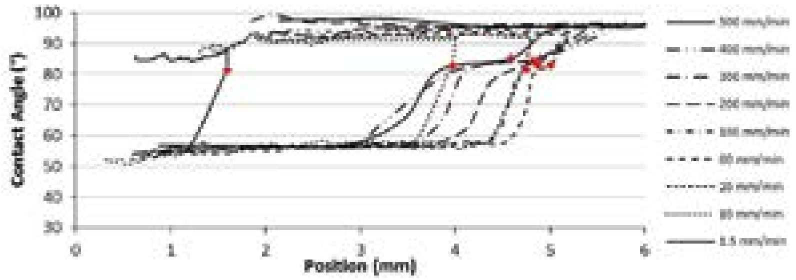
FLAX FIBRE COMPOSITES

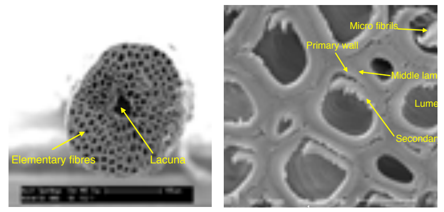


Through the networking enabled by the framework of the CELC (European Flax and Hemp Confederation), new activities have started concerning flax and hemp fibre composites. Postdoctoral researcher Joris Baets, working as a technical advisor for CELC, and Ignaas Verpoest are continuously monitoring new developments in flax fibre extraction, preforming and composite processing technologies. Within the framework of the European Scientific Committee of CELC, they are preparing a new, standardised test method for flax fibres ("impregnated fibre bundle test"), and have developed a template for datasheets for flax fibre preforms. CELC organised two workshops in collaboration with JEC (in Paris and Leuven) on flax fibre composites. Another highlight has been the 2012 publication of a book on flax and hemp fibres, with the title "Flax and Hemp Fibres: a Natural Solution for the Composite Industry", written by members of the ESC of CELC, and coordinated by Joris, Ignaas and Julie Pariset (CELC). It is published by JEC (Journée Européenne des Composites).

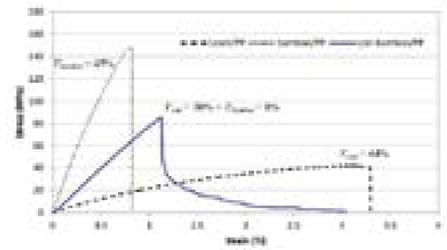
In 2011 the European project Biobuild started, coordinated by NetComposites (UK), with the aim to develop durable, moisture resistant bio-composites, primarily based on flax fibres, for applications as interior and exterior panels in buildings. Various treatments have been developed to increase the fibre-matrix adhesion, the internal adhesion between the elementary fibres, as well as the moisture resistance. The aim is to develop fully bio-based composites, with, for example, the furan resin systems of Trans Furans Chemicals. Two PhD students are working on this project, Dieter Perremans and Farida Bensadoun (partially with a grant from the Canadian government), together with Joris Baets as postdoctoral researcher. Malika Kersani, who will finish her PhD in Algeria, is also working on flax fibre composites, doing damage and fatigue investigations.

Advancing and receding contact angles at different immersion velocities. The red tilted squares are the measured static angle after 20 seconds of relaxation

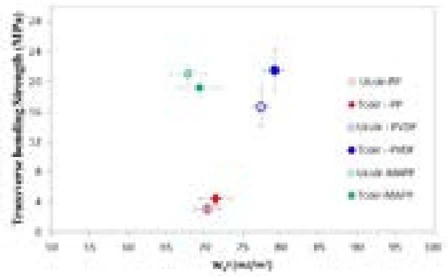




Details of the microstructure of coir fibres, showing the micro-fibril orientations inside the elementary fibres



Tensile behavior of coir fibre /bamboo fibre hybrid composites, where an interesting synergy is obtained



Results showing higher interfacial adhesion of coir-PVDF than coir-PP due to higher physical adhesion. Chemical bonding leads to a stronger coir-MAPP interface than that of coir-PP *(PhD thesis of Ngoc Tran Le Quan)*

HEMP FIBRE COMPOSITES

Through the CELC community, the Composite Materials Group is also participating in the European MultiHemp project, started in 2013. In this project, partners in the universities of Wageningen and York are trying to breed better species of hemp for their fibres. The role of the CMG is to evaluate the fibre performance in composites together with the universities of Bremen (Prof. Jörg Müssig) and Aalto University in Helsinki.

COIR FIBRE COMPOSITES

In his PhD which he finalised in 2013, Ngoc Tran Le Quan has focused on studies of the fibre-matrix interface in coir fibre composites. He also did some investigations on the fibre microstructure and the mechanical performance of coir fibres and their composites. As expected, based on the very high strain to failure of coir fibres, the fibres have potential to create impact resistant composites. Also, very interesting results were obtained with coir fibre – bamboo fibre hybrid composites, where an interesting synergy is obtained between the stiff, but brittle bamboo fibre and the less stiff, but tough coir fibre.

BIO-COMPOSITES AT SLC

Between 2010 and 2012, Aart van Vuure finalised his direct commitments as industrial advisor for Sirris (which had in the meantime created together with KU Leuven the Sirris Leuven-Gent Composites Application lab (SLC)), by executing a so-called TIS project (Technological Innovation Stimulus) on bio-polymers and bio-composites. Amongst different initiatives, a one-day congress was organised on bio-polymers at the end of 2011. Also, together with ITA Aachen and Centexbel, a European Cornet project was run by SLC to develop flax fibre-PLA composites. Work has focused mainly on producing fibrous preforms based on mixed flax and PLA fibres. The role of SLC has been composite consolidation, thermoforming and mechanical characterization. A demonstration chair was developed for the GroepT Formula Student racing team (GroepT is part of the KU Leuven Association). Recently, in 2013, SLC has started a new Cornet project with the same partners, run by Linde De Vriese, on self-reinforced PLA composites (Bio-SRPC).

PROCESS AND APPLICATION DEVELOPMENT

Since the creation of SLC, the Sirris-Leuven-Gent Composites Application Lab, described previously, we have been able to provide scientific and technological support to the industry in the form of advice, as well as short- and long-term research, often involving the joint efforts of SLC and the Composite Materials Group. The integration of all masters programs into the university also affects the capacity of the department MTM and the Composite Materials Group, encouraging more process and application development work.

The university colleges, with their clear focus on application and implementation oriented research, are now integrated within the university. Therefore, the industrially oriented composites masters projects of students from the former university colleges KHBO (Frederik Desplentere), KAHO SL (Pascal Lava), Thomas More campus De Nayer (Jan Ivens), Groep T (Aart Van Vuure) and KHLIM (Bert Van Bael) will now be coordinated at MTM. The integration will officially take place in October 2013, but the Composite Materials Group has already developed intensive collaborations, illustrated already in the previous chapter by the PhD of Frederik Desplentere and the re-integration of Jan Ivens, and further shown in the next paragraphs.

SAMSONITE – RECENT DEVELOPMENTS

After the successful launch of the Cosmolite suitcase, Samsonite further wanted to improve their composites suitcases making them even lighter and searching for other concepts (for instance replacing the zipped closure by real locks). A new IWT-project was launched, led by Rik Hillaert at Samsonite and Joris Baets as a postdoc researcher at KU Leuven (this research forms the second half of his function, combined with his half-time position as technical advisor to CELC). The goal of this project is to develop self-reinforced composites with higher stiffness while keeping the same toughness, a difficult task , requiring new, even hybrid material solutions. Again, it was an exercise in 'concurrent engineering,' because new designs were developed simultaneously, and many different finishing options (printing, textile exteriors, ...) were explored. In the meantime, Samsonite launched new designs (Cubelite) and even lighter versions (Firelite), always innovating in order to stay ahead of the competition in lightness, strength and toughness!

Jan Ivens

Jan Ivens was one of the first MTM-students that made a master thesis on composites in 1987. He started a PhD on the same subject (interfaces in composites), but simultaneously guided the emerging research in textile composites. Consequently, his post-doctoral research after obtaining his PhD in 1993 was not on interfaces, but on textile composites, making the first steps in the mechanical modeling of textile composites that would be further developed by Stepan Lomov. He initiated the first research on natural fibre composites in 1995 and was involved in many short industrial projects, resulting in the start of the Technology Advisor Service in 1999 whilst becoming the first innovation coordinator of the department MTM. The next logical step was to move to industry in 2001 as R&D and Engineering Manager of the the Arplama Group, whilst remaining a part-time lecturer at KU Leuven. In October 2005, Jan returned to academia full time, first at the Sint-Lucas Architecture department, and later in 2007 at campus De Nayer (Engineering Technology), which allowed him to return to composites research at the department MTM by assuming responsibility for the "process and application development" research line, involving research on improved, cost-effective manufacturing processes and novel applications for composites and foams. From 2011 to September 2013, he was the head of the Department of Engineering Technology at campus De Nayer, and is currently involved in the new, Faculty of Engineering Technology of KU Leuven, as chairman of the assessment committee (since 2012) and coordinator of research profiling (since 2013).

Advertisement of Cosmolite

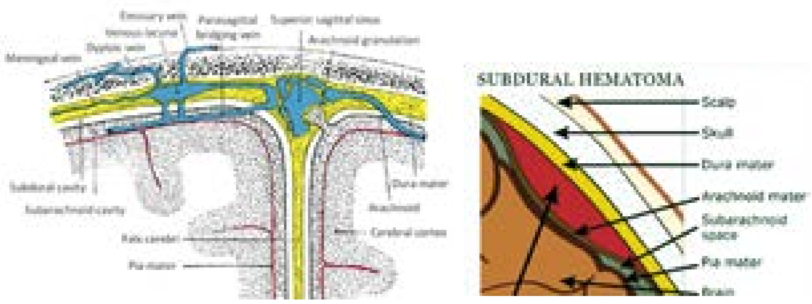
RESEARCH ON FOAMS

Although foams are a special kind of composite (a solid material and a gas), they have always been of interest in the Composite Materials Group, mostly as a core material for sandwich panels. Aart Van Vuure studied the effect of the foam morphology on the mechanical properties of 3D-woven sandwich panels in the early nineties, and in the last few years, foams have regained interest in the Composite Materials Group. During a short stay, Mehmet Karahan (2011) even studied the static and impact behavior of 3D-woven sandwich panels, reviving the work or Aart and Hermawan Judawisastra! Nano-reinforced PP and PU foams were investigated in the NANCORE project and the PhD work of Oksana Shishkina (described in the previous chapter). In 2012 a new IWT project was started in collaboration with Deceuninck (Tom Houthoofdt , Geert Demeurisse and Nick Aspeslagh) and the Department of Chemical Engineering at KU Leuven (Peter Vanpuyvelde) to develop low density PVC foams. In the framework of this project, Oksana Shishkina continues her investigations of the structure-property relationship of polymeric foams.

ANISOTROPIC FOAMS FOR THE INCREASED ROTATIONAL ACCELERATION PROTECTION OF HELMETS

Since the research on 3D-knitted fabric composites in the nineties (PhD of Dirk Philips), the Composite Materials Group has been involved in research on bicycle helmets and body protection, and had developed good contacts with the Biomechanics division of the Mechanical Engineering department (Prof. Jos Vander Sloten) and the Department of Neuroscience (Prof. Jan Goffin, Prof. Bart Depreitere).
In the early 2000s, the Department of Neuroscience had become interested in research regarding the cause of acute subdural hematoma (ASDH), a life-threatening head injury that was often found in victims of bicycle collisions. Together with the Division of Biomechanics, they determined that rotational acceleration, originating from the tangential component of impact forces during a collision, was the cause for ASDH. This rotational deceleration causes the skull to rotate relative to the brain within, resulting in a tensile force in the veins that bridge the space from the brain to the skull. These tensile forces lead to rupture, and a very fast bleeding in the subdural space of the head, the so-called acute subdural hematoma.

Once the cause was determined, the CMG group was called upon to devise a way to reduce the tangential forces transmitted to the head and thus the rotational acceleration. Initially led by Ignaas Verpoest, the preliminary idea was to use a material with a low shear resistance, allowing the material to shear easily while absorbing energy in compression. The first proposal was to use the 3D knitted materials that were developed earlier, but while they did have low shear resistance, they suffered other disadvantages, like the high cost of the 3D-textile. The idea then turned to using anisotropic foam materials that had their cells



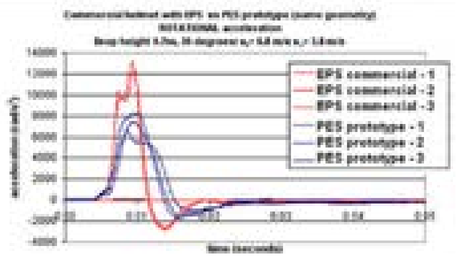
The bridging vein complex that connects the cerebral cortex with the dura mater. If the bridging vein ruptures during a rotational impact, it causes a bleeding between the dura mater and the cerebral cortex, a subdural haematoma.

oriented perpendicular to the head surface leading to reduced shear stiffness of the foam. Kelly VandenBosche began her PhD-research on learning more about anisotropic foams, their structure and properties and how they could be evaluated with regards to a helmet. She developed two test machines for testing foams: a combination shear-compression tester for investigating combined shear-compression loads in static situations, and a rotational impact tester for evaluating helmets under a rotational impact situation (non-perpendicular impact). First experiments on anisotropic PES-foam proved that anisotropic foams indeed reduce the rotational accelerations during oblique impact.

Since PES is too expensive, alternative anisotropic foams had to be developed. In the margin of the ongoing NANCORE project, Ignaas Verpoest discussed this with Prof. Miguel Ángel Rodríguez Pérez of the Cellular Materials Laboratory of the University of Valladolid, who saw possibilities in the use of cross-linked HDPE. Kelly developed a production method to obtain anisotropic HDPE foam on a small scale, in the framework of an IOF leverage project.

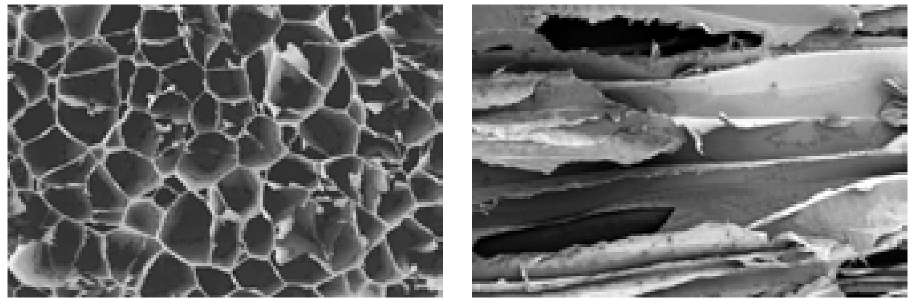
This work was very promising, yet preliminary, and a new FWO-project involving Jan Ivens, Prof. Bart Depreitere (Department of Neuroscience) and Prof. Vander Sloten (Biomechanics division) has recently been granted. In 2013, Yasmine Mosleh started her PhD, continuing the development and evaluation of anisotropic foams. Together with the University of Valladolid, the HDPE foam formulations and the manufacturing methods are being further improved and readied for upscaling, taking into account that a curved shape is needed. Simultaneously, the test methods for foam and helmet characterisation are being optimised, aiming at developing test standards for the certification of future generation bicycle helmets. This is being carried out in close collaboration with Dr. Peter Halldin of the Department of Neuronics at the Royal Institute of Technology in Stockholm, Sweden.

Collaborations between the Composite Materials Group, Neurosurgery, and Biomechanics are still very active, we are working together to try to better understand the mechanics of brain injury by performing specialised material tests veins in the PhD of Zhaoying Cui (with Jos Vander Sloten as promotor), and by integrating information from all three disciplines into a head/helmet model to be able to predict head injuries and evaluate new helmet technologies.



The impact test results on anisotropic foam show improved impact behavior

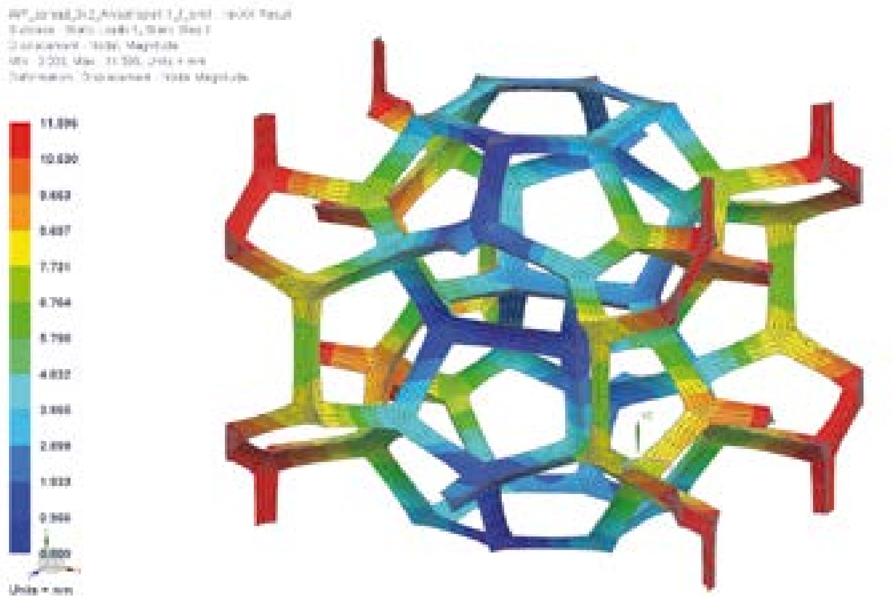
The microstructure of the anisotropic foam



HYBRID FOAM: COMPOLITE®

After Frederik Desplentere, Bart Buffel would become the second researcher at the university college KHBO to start a PhD in the Composite Materials Group. However, the circumstances have changed favorably: whereas Frederik had to combine his PhD-research with his teaching tasks within the college, Bart could fully concentrate on the PhD research since he won a Baekeland-grant. Such grants are awarded for PhD-studies in the framework of joint industry-university collaborations. The company Recticel, leader in PU-foams, had developed a new concept of a hybrid foam, Compolite®, for producing formable sandwich panels: a flexible open cell foam is used to support glass mat skins, the system is impregnated with a PU-resin and enclosed in a mould where the PU-resin starts foaming into a closed cell foam, acting as core material for the sandwich structure. Bart is not only optimizing the material, but mainly focusses on developing innovative models for analysing the (hybrid) foam properties.

A picture of an open cell foam (left) and a model of a representative section of the foam (right)



THE MATERIAL IS THE MECHANISM: SHAPE MEMORY POLYMERS, COMPOSITES AND FOAMS

The department MTM has a long tradition in research on shape memory alloys, but for the applications Carl De Smet (noumenon) had in mind, the 8 % deformation during transformation was insufficient and the cost of the NiTi-alloys was too high. Carl wanted to use them in design applications like chairs, seats and tables, so instead, he considered using shape memory polymers (SMP) which show much higher deformations (50% and more) but they show very low shape recovery forces, which limits their applicability to small components.

Jan Ivens suggested reinforcing the polymer with fibres to increase the recovery forces, and in the framework of an OPK (Research Platform for Arts), they developed fibre reinforced shape memory polymers using resin transfer molding. Mathieu Urbanus and Maarten Fabré investigated the thermomechanical behaviour of the SMP, showing that shape recovery forces are increased by a factor of 20 when using a woven glass fabric. A 250 mm large scale model of a chair was made, the largest shape memory composite to date.

Although the results were promising, the transformation times were very long. PhD student Iulia Bocsan (2011) investigated the possibility of improving the transformation times using filler materials in combination with resistive and microwave heating. Carbon nanotubes allowed fast heating in microwaves, but the poor dispersion of the CNT's resulted in hot spots in the composite.

Scale model of a self-deploying chair based on shape memory polyurethane foam

A finger like tool is run over a flat metal plate and creates a 3-dimensional shape by plastic deformation

The limited availability of the shape memory thermoset resins forced us to look for alternatives, which were found in shape memory polyurethane foam, provided by the Belgian company Recticel: instead of increasing the material stiffness to achieve shape recovery, the weight of the material is reduced, while maintaining a high moment of inertia to obtain the necessary rigidity. Current research is aimed at improved transformation times using embedded carbon fibres, and at surface coatings for increased scratch resistance.

REDUCING TOOLING COST USING PLATE BASED MOULDS

For smaller series sizes, the cost of tooling can be a bottleneck for composite manufacturing. In the IWT-project MEPLAMAT, the use of plate forming techniques to produce complex, shaped metal plates for composite tools was investigated. Techniques like single point incremental forming (SPIF), where a flat metal plate is shaped without a die, using a forming finger, two point incremental forming (TPIF), where the plate is formed on a cheap die, and more conventional techniques like spinning and plate bending were compared and evaluated by the department of Mechanical Engineering (Prof. Joost Duflou) for the construction of tools for spray-up, thermoforming, resin infusion and resin transfer moulding.

The design, construction and evaluation of the tools was done by project researchers Raf Appermont (KHLIM) and Jan Bens (Thomas More, campus De Nayer).

Plate mold technologies were developed for several composite manufacturing techniques like vacuum forming, vacuum infusion and resin transfer molding. Multiple insert tooling can increase production rates by a factor of 2, while the use of double shell tools allows fast cooling and heating, which could further increase production rates. Further research and experience is needed to speed up the process of optimizing the part shape so metal plate tooling can easily be applied.

OPTIMIZING THE THERMOFORMING PROCESS

The research in the framework of the MEPLAMAT project pointed out the importance of adequate temperature control of the thermoforming mould. Moreover, the process parameters for thermoforming are usually determined based on experience and trial & error, resulting in suboptimal processes and lengthy optimisation procedures, despite the existence of simulation software. The goal of the PhD of Bart Van Mieghem is to develop a methodology to optimise the process parameters for thermoforming by means of intelligent experimentation. This is achieved by in situ measurement of the strains in the composite plate during thermoforming, by means of digital image correlation (MatchID, developed by Prof. Pascal Lava (KAHO SL)), allowing direct calculation of the local plate thickness, usually the limiting factor in thermoforming. The technique is used to optimise the temperature distribution of the plate during thermoforming.

LOOKING TO **THE FUTURE**

Since its origin, more than three decades ago, the Composites Materials Group in Leuven has seen some remarkable evolutions on its path to developing the unique identity it has today. Several of the distinctive characteristics that define the Group are highlighted below. Over the years, the Composite Materials Group has grown steadily, and research has become focused into the four directions mentioned earlier in the text. Each of these research directions is now progressing, and the future vision for each of these fields, their missions, have been developed based on the insights acquired about the nature, growth, and necessary innovations for the progression of the composites field.

IDENTITY OF THE COMPOSITE MATERIALS GROUP

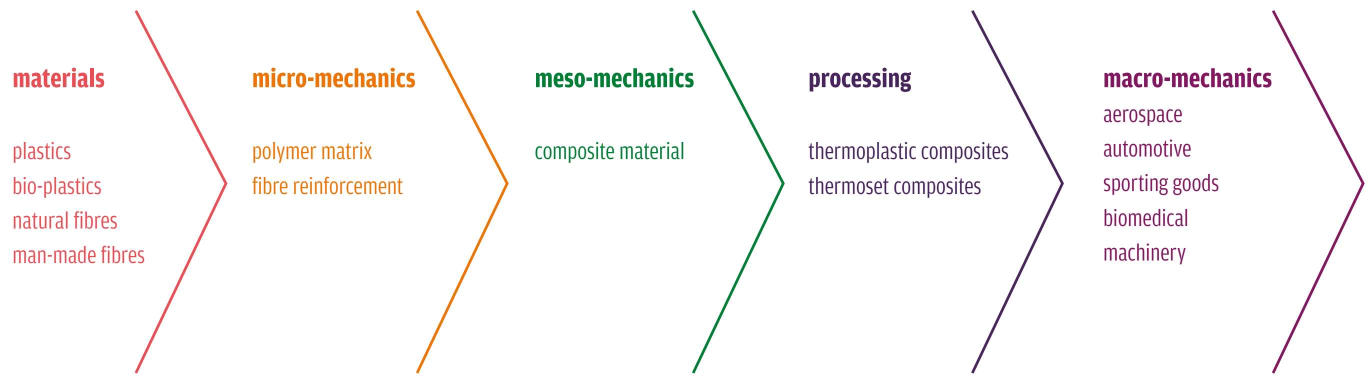
APPROACH: FROM MATERIAL CONSTITUENTS TO PRODUCT DEVELOPMENT

The Composite Materials Group was founded as part of the Metallurgy and Materials Engineering department. Because of this, research in the group has always been focused as much on the materials science as on the processing and mechanics of composites. More fundamental research into novel fibres or matrix materials takes place next to the analysis of the mechanical behavior of composites and studies exploring the processing of these materials. Occasionally, projects are even carried on into the 'product development' stage, e.g. the Samsonite suitcase and the bicycle helmet project.

The fact that research in the Group spans the whole spectrum from the material constituents to product development leads to a unique, multidisciplinary mix of researchers and projects.

HIERARCHY OF SCALES: FROM NANO TO MACRO

For the development of novel materials with tailored performance, and analysis of existing high performance composite systems, researchers in the group use advanced simulation tools and characterization techniques that cover the structural/hierarchical levels from the nanometer to meter scales. The emphasis is placed on the structure-defined material behavior. The latter is a result of complex processes that unravel on different length and time scales and are intimately linked to the material's internal structure. The final performance is dictated by the geometry of a part on the macro-level, by the reinforcement architecture on the meso-level, by the arrangement of fibres inside yarns on the micro-level, and by the polymer morphology and fibre-polymer interface on the nano-level.



Research in the Composite Materials Group: ranging from individual material constituents to development of applications

INTEGRATION OF EXPERIMENTAL AND MODELING WORK

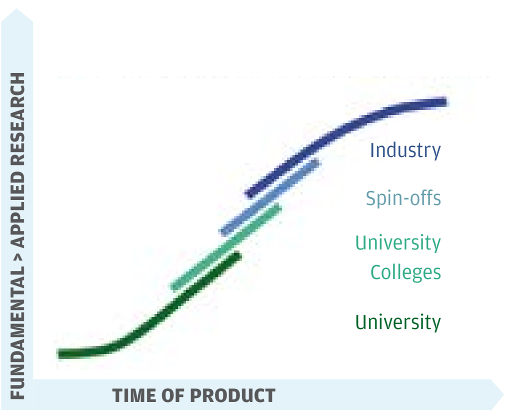
The modeling and simulation of real structures is advantageous for obtaining information about composite materials without costly manufacturing processes. Some of the features of composites, such as the interaction between fibres and matrices, can be understood by performing simulations with various types of models. The composite industry is very interested in further development of such models and simulations in order to most optimally design composite structures while reducing design and testing costs. The process of developing reliable models is always performed in the light of experiments to achieve more realistic simulations.

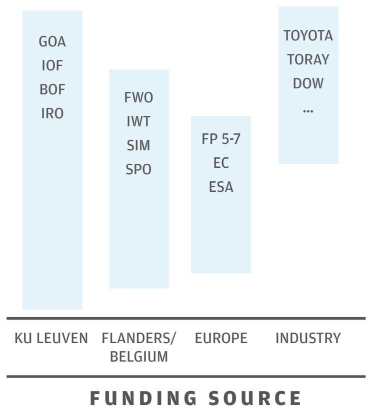
INTEGRATION OF FUNDAMENTAL AND APPLIED RESEARCH

Research in the Composite Materials Group ranges from fundamental studies to applied and/or oriented projects, and is funded by different sources comprising Europe, Belgium, Flanders, KU Leuven and industrial cooperation. The balance between long-term fundamental studies, middle-term applied research and short-term industry-driven work is maintained via a balanced use of these funding sources.

For instance, the fundamental research is supported by the Belgian (IUAP) and Flemish (FWO) government, by KU Leuven and by the European Commission via the 5th-7th Framework Programs. The middle-term applied research, which almost always is combined with fundamental studies, is also supported by the Flemish (IWT, SIM), Belgian (Belspo) and EU sources, as well as by direct funding from industry (Toray, Huntsman, Nanocyl, Deceuninck, SNECMA, etc...). In addition, short term, industry-driven problems are directly addressed by carrying out dedicated test series and providing consultancy (projects of half-year or less). In order to serve the local industry even more efficiently, SLC, the Sirris-Leuven Composites Application lab was founded in 2010.

Research can be executed by different institutions, depending on the nature of the study.
Very fundamental research is mainly done by universities, while the pure product development is usually the work of industrial R&D divisions or spin-offs, as illustrated on the left. The bar chart on the right indicates which types of funding sources are possible for the different types of research.





COLLABORATION MODELS WITH INDUSTRY

As a research group in an engineering faculty, collaboration with industry is evident. Most often, such collaboration happens within the framework of multi-partner projects funded by the regional (Flemish) or European government. In the past 30 years, the Composite Materials Group has been collaborating with more than 120 companies worldwide.

More recently however, direct collaboration with industrial partners has become more important. Two models for this are used. In one model, the company directly funds a Composite Materials Group researcher on a topic of mutual interest; examples of such collaboration are Hermès (on silk fibres), EADS (on textile composites), and Deceuninck (on wood fibre composites) among others. In the other model, the company will send one of their own researchers or engineers to KU Leuven for an extended period, not only to learn from the ongoing research and hence the broad knowhow of the Group, but also to make use of the extensive experimental facilities of the composites lab. This was the case for companies like Toray (carbon fibre thermoplastic composites), Huntsman (new PU-based thermoset resin), Nanocyl (carbon nanotubes), and in the early days DSM (on basic composites technology).

COLLABORATIONS WITHIN UNIVERSITY AND WITH UNIVERSITY COLLEGES

Being the chairman of the Leuven Materials Research Centre (LeuvenMRC), Ignaas Verpoest has always been a strong supporter of interdisciplinary collaborations within the university. Already at the start, in the early 80's, the project on composite tennis rackets was a collaboration with the Department of Mechanical Engineering, utilizing their knowhow in vibrational analysis and damping,. In the 90's this collaboration expanded towards manufacturing related issues like filament winding and compression moulding, resulting in the creation of the formal collaborative platform LCPC (Leuven Composites Processing Centre) in which the Chemical Engineering department also joined.

The framework of LeuvenMRC, of which Ignaas has been a chairman since the start in 2006, provided a much larger platform for trans-disciplinary collaboration involving 20 different materials related research groups from three different faculties. Apart from Mechanical and Chemical Engineering, the main collaborations are with the departments of Chemistry, Computer Science and Physics, and with the faculty of Bio-engineering.

The Composite Materials Group has also been one of the frontrunners in intensive collaboration with the independent university colleges which are linked to KU Leuven, through the "KU Leuven Association." Frederik Desplentere was one of the first university college staff members to obtain a PhD at KU Leuven while working as a researcher at KHBO. Nowadays, Frederik together with Jan Ivens (Thomas More, campus Denayer) and Aart van Vuure (Groep T) are full members of the Composite Materials Group, while also teaching and conducting research at their respective colleges.

PARTNERS WITHIN THE INDUSTRY

BENTELER-SGL
BEKAERT
BEKINTEX
TECHSPACEAERO
HUNTSMAN
ECONCORE
LMS
COEXPAIR
NANOCYL
SAMSONITE
RECTICEL
EASN
ACROSOMA
ASCO
LM-WINDPOWER
EADS
FIBROLINE
ALSTOM
DAHER-AEROSPACE
ESI-GROUP
HEXCEL
DASSAULTAVIATION
ONERA
RENAULT
CEA
EXTENDE
ARCELOR-MITTAL
CELC
BAM
POLYMADEITT
R-TECH
QUICKSTEP
VOLKSWAGEN
MERCEDES-BENZ
AIRBUS
VOLUMEGRAPHICS
FRAUNHOFER
SAARTEX-WAGENER
DAIMLER-CHRYSLER
PROPEX
CYCLICS
BEINER
PEISE
STRUCTOFORM
INASCO
VAMP-TECH
PIAGGIO AEROINDUSTRIES
FIAT
AZIMUT-BENETTI
TOYOTA
TORAY
TENCATE
AIRBORNE
NLR
DOW
EUROCARBON
BUILDAIRINGENIERÍA-AND-ARQUITECTURA
NANOZAR
CIMNE
FIDAMC
IMDEA
BAX&WILLEMS
VOLVO
SKF
SWEREA-SICOMP
ALUSUISSE AIREX
REGLOPLAS
VICTREX
BOMBARDIER
FOCAL
3TEX
OWENS-CORNING
GENERAL ELECTRIC
TELEDYNE SCIENTIFIC
QUADRANT
SAFRAN
NETCOMPOSITES
3XN
ACCIONAINFRASTRUCTURAS
HOLLANDCOMPOSITES
TRANSFURANSCHEMICALS
ARUP
DSM-RESINS
AMORIM
TNO
LNEC
SHR
FIBREFORCECOMPOSITES
DECEUNINCK
ENGTEX
SAAB AEROSPACE
JOHNSON CONTROLS
POLYVISION
LINEO
COURTAULDS
ICI
PARABEAM
FOKKER
BRITISH AEROSPACE
VELDEMAN
IFREMER
INTERMARINE
METALLEIDO
MÜLLER TEXTIL
IPA
JOHNSON&JOHNSON
SMITH&NEPHEW
SOLICO
GE PLASTICS
ARPLAM
EUROCOPTER
MILLIKEN
TEXDEM
HERMÈS
APOPO
SHELL
STAVELSE

COLLABORATIONS WITHIN UNIVERSITY AND WITH UNIVERSITY COLLEGES

EXTENSIVE NETWORK OF RESEARCH PARTNERS AND INVOLVEMENT INTO THE COMPOSITES COMMUNITY WORLDWIDE

As will be explained further in this book, worldwide networking is another key aspect of the identity of the Composite Materials Group.
The many European projects in which the Group has participated have offered an excellent opportunity to initially establish a wide European network of universities and industries. But cyclically, this network was also instrumental in conceiving and successfully submitting new European project proposals, as has been explained in the story on the string of EU-projects starting with AFICOSS and still ongoing with HIVOCOMP. The one-year European Master Program, EUPOCO, in the 90's has been another catalyst for creating our vast European network.
The worldwide network was gradually built up in two ways. Firstly, longer stays of Ignaas Verpoest as a visiting scientist or professor in USA (Stanford), Japan (Kansai University), Switzerland (EPFL), Indonesia (ITB) and Vietnam (Cantho University), have been a fruitful ground for establishing deep collaborations and exchanges within these countries. Later on, Stepan Lomov extended this approach with teaching missions at Sicomp (Sweden), Politecnico di Milano, Osaka University, St-Petersburg State University of Technology and Design and Nanyang University (Singapore).

Secondly, all members of the Composite Materials Group have been very active at presenting their work at international conferences. We have also been actively involved in helping with their organization (Ignaas has been involved in ICCM, ECCM, SAMPE-Europe, Stepan in ECCM, ESAFORM, FPCM) and also helping to create new, topical international conferences like the early composites workshops with Steve Tsai and George Springer, and the conferences TEXCOMP and IPCM *(see also the chapter 'Networking')*.

SERVICE TO SOCIETY, SCIENCE COMMUNICATION, PUBLIC AWARENESS

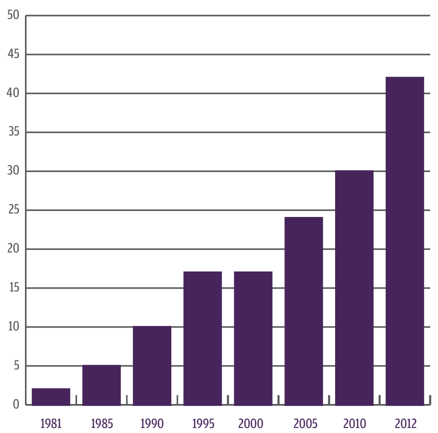
Between obtaining his master's degree (1972) and starting his PhD (1976), Ignaas worked as a pastor in the University Parish of KU Leuven on 'science and society' issues. It was the time of emerging environmental awareness (the Report of the Club of Rome had just been published) and the pacifist movements in the aftermath of the Vietnam war and during the height of the Cold War ('the schizophrenia of working for war').

Since then, the social and political responsibility of scientists and engineers has always been an underlying concern, and was included in the daily responsibility of leading a research group on composite materials. The potential offered by composites for weight reduction and hence lower energy consumption was a perfect answer to the increasing need for ecofriendly technologies. While this message was evident throughout the philosophy and day-to-day activities of the Group, it was Ignaas' impression that his message did not yet penetrate sufficiently into European society. This was the start of the Composites-on-Tour initiative (2002 and 2006), which reached more than 85.000 people in all possible places (from beaches to museums), and for which Ignaas obtained the Descartes Prize for Science Communication in 2004.

It was equally important to inform the public at large about the results of large research projects and other successful innovations. The Composite Materials Group has been a frequent guest in the university magazine 'Campuskrant,' and in the national newspapers and TV-journals.

A STEADY GROWTH IN RESEARCHERS AND RESEARCH PROJECTS

Over the past three decades, the Composite Materials Group at KU Leuven has grown steadily from the initial 2 (Ignaas Verpoest as postdoctoral researcher, Martine Wevers as first PhD-student) to 35 to 40 people. In recent years, the composition has stabilized with around 20 to 25 doctoral researchers, 5 junior and 5 senior postdocs (the latter splitting their time between research and instruction, either part-time professor at KU Leuven or lecturer at one of the associated university colleges). The Group furthermore welcomes an average of 5 visiting researchers from industry or partner universities and an increasing number of Master students (in recent years around 15) each year. Last but not least, 4 technical staff members of the department are responsible for keeping the composites lab functioning at a level that allows us to perform tests according to the highest international standards.



The evolution of the number of researchers being part of the Composite Materials Group over the years.

A STRONG INTERNAL ORGANIZATION, WELL EMBEDDED IN THE DEPARTMENT

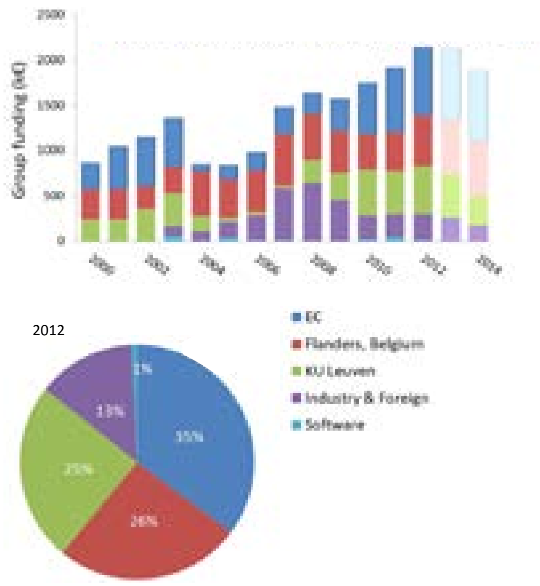
As the number of researchers was steadily growing, the internal organisation of the Composites Group had to be 'professionalised'. Already in the early 90's, a "start-up day" at the beginning the academic year was organized. All researchers and technicians spend one day outside the department to go in detail through the planning of the upcoming year. Not only tasks are distributed (organization of lab sessions, supervision of master students, responsabilities for lab equipment...), but the performance of the group during the past year is evaluated in sometimes vivid discussions.

During the academic year, the whole group meets every other week for one hour, to review the planned activities and solve technical and organizational problems. Moreover, a monthtly 'CMG-seminar' is organized: at least once a year each CMG-researcher presents his ongoing work, after which not only the scientific contents are discussed, but also feedback is given on the presentation style. In this way, PhD-students get an on-the-job training in presentation skills! Finally, more strategic and long term planning issues are discussed monthly in the meeting of the senior researchers (Ignaas, Stepan, Jan, Aart and Larissa).

A DIVERSIFIED PROJECT FUNDING

Research in engineering has a diversified funding structure. The direct funding of salaries by the university has always been very limited. Currently it accounts for the professorship position of Ignaas Verpoest, the part-time professorship of Stepan Lomov (10%) and partial funding of technical and administrative staff. Recently, the involvement of the university college staff members Jan Ivens, Aart van Vuure and Frederik Desplentere (who will become fully integrated into the university system from September 2013 on) has alleviated the difficult situation of too few permanent staff members guiding a large research group.

Indeed, all the doctoral and postdoctoral researchers are financed on projects which are acquired on a competitive basis! This situation is a big, yet achievable, challenge for the Group. The steady growth of the Composite Materials Group has been realized through a deliberate strategy of well diversified funding sources. As can be seen in the pie and bar charts, about one third of the financing is acquired in the highly competitive European Commission R&D programs (specifically FP-7), and one quarter each from the equally competitive funding programs of the Flemish government and the KU Leuven. Finally, over the several last years, ten to fifteen percent of the funding is provided directly by industry, and some foreign governments (the latter as research grants).



The evolution of the budget of the Composite Materials Group over the years. The available resources have been (and keep) growing steadily, and a nice balance between the different funding sources is maintained.

Keeping up a total yearly funding of about €2 million is a challenging task, but the fact that the Composite Materials Group was able to do this over the past 5 years is a proof that this diversified funding strategy, combined with the high level of research, seems to work. Moreover, it should be emphasized that a healthy balance between more fundamental projects on one hand, and more application oriented ones on the other hand, has always been pursued. It is hard to represent this subdivision in numbers since there is significant overlap, but a rough estimation leads to one third 'more fundamental' and two thirds 'more application oriented' projects, a healthy balance indeed.

CLOSE INTERACTIONS WITH STUDENTS

The courses given by the Composite Materials Group emphasize a strong interaction between student and lecturer. This strategy is supported by different practical sessions strongly related to the courses, in which the Bachelor and Master students are intensively guided by PhD students and post-docs. In one practical session, the students must apply what they've learned in their course on the composite laminate theory in order to design a skateboard. The students then learn about various processing techniques by actually producing their laminates. Finally, mechanical testing is performed on the skateboard material that they have designed and produced, and they are required to analyze the actual laminate properties and compare them to their design. In another practical session, the students are assigned an innovative composite material and are asked to learn about the material and research a possible application for it. Several students also perform a Bachelor thesis project on a composites related subject where they get to learn about composites in a more in-depth and focused way before beginning their Master studies.

With this methodology, the student is prepared for the rigorous research necessary for a successful Master thesis project. The students appreciate this approach, which is reflected in the high number of students choosing composite related subjects for their Master thesis. During the Master thesis, a more independent approach is stimulated, of course under the guidance of a PhD student or post-doc who supervises their work. By this approach, the student is well prepared for professional life.

(Below left) **The Composites group on a weekend trip in the Ardennes (1995)**
(Below right) **Dinner party in the early 90s**

(Above left) **An adventurous team building day in Dinant, September 2011**
(Right, top) **Indoor climbing (2013),**
(Right, bottom) **Indoor skating (2012)**

Party at Ignaas' house, 2nd of July 2011

The subject of one of the student's practical sessions is the design and testing of a skateboard. Students get very involved in these sessions, and sometimes this results in very creative output.

ACTIVE SOCIAL LIFE

Members of the Composite Materials Group like to work together, but also to spend their free time together. They organize various events including trips to different places in Belgium, dinners in private residences, casual discussions at pubs and also numerous sports activities (ice-skating, climbing, football, bowling, cycling, etc). Those who do not play sports are always welcome to cheer for their colleagues.

Among the most popular activities are international evenings, where members of the group exchange knowledge about their countries: culture, history, life style and, of course, food. Trips together to conferences and

International Evening: people present their country of origin and bring some local food, and share their culture with the rest of the Group. International evening 28th of april 2010 and international evening of 24th of November 2012

(Top) **The composites Group in the early 90s at the start-up day of 1994**
(Top right) **The Composite Materials Group during the 2012 start-up day in the Musem M of Leuven, in front of an art work of Sol LeWitt.**
(Right) **CMG-start day in 1990, in the woods around Leuven**
(Far right) **CMG-start day in 2009, in the HIVA continuing education facilities in Pellenberg**

exhibitions are anotwher way to form and strengthen the friendships within the group by spending time together listening to enlightening presentations, but also exploring new cities and countries, admiring art and historical buildings, and at the end of the day eating dinner in good company. What could be better?

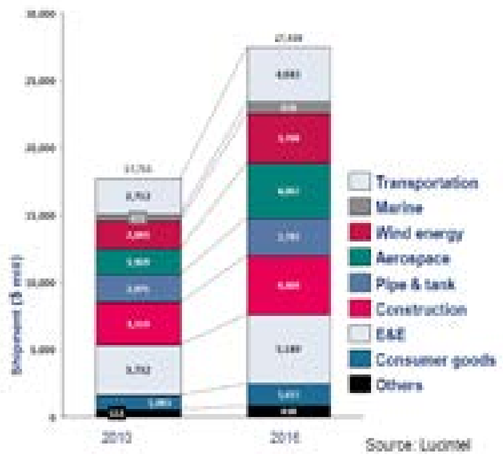
These activities help to build close relationships and they have a positive effect on the research work. Difficult scientific problems require a team effort and an environment where knowledge and ideas are freely sheared. The Composite Materials Group is proud to have cultivated such environment. People even stay in touch for many years after they leave MTM.

CULTURAL DIVERSITY OF THE GROUP

From the early beginning, the Composite Materials Group has attracted researchers from around the world who have either conducted their PhD here or spent a period of time in the group as a post-doc or visiting researcher. Over the years, people of 40 different nationalities have been a part of the Group. Because the industrial and academic conditions and the local 'composite' interests in many of these countries are substantially different from those in Belgium, this type of international environment naturally also encourages a mutually enriching exchange of backgrounds, interests and cultures.

Members of the Composite Materials Group have come from all over the world.

ALGERIA
AUSTRALIA
BANGLADESH
BELGIUM
BULGARIA
CANADA
CHINA
COLOMBIA
CYPRUS
CZECH REPUBLIC
EGYPT
FRANCE
GERMANY
GREECE
HONG-KONG
INDIA
INDONESIA
IRAN
ISRAEL
ITALY
JAPAN
KENYA
LATVIA
LITHUANIA
MADAGASCAR
MOROCCO
PERU
POLAND
ROMANIA
RUSSIA
SINGAPORE
SLOVENIA
SPAIN
SWEDEN
SWITZERLAND
THE NETHERLANDS
TUNISIA
TURKEY
UNITED STATES OF AMERICA
VIETNAM



Global composite materials turnover growth per market segment *(source; Lucintel: Growth Opportunities in Global Composites Industry, 2011)*

VISION FOR THE FUTURE OF COMPOSITES

APPLICATION DEVELOPMENT

The composites market has seen strong growth in recent years, not only in aeronautics, but also in other industries, e.g. the wind energy industry. The predictions for the coming years are equally promising; A market study by Lucintel predicts a 50% growth of worldwide composites turnover by 2016, composed of growth in many different markets.

Unfortunately, Flanders is currently lagging behind in applying the newest technologies, and the traditional composite companies are straining to keep up with the trend. For Flanders to stay globally competitive in this market, new companies will need to be founded, or existing companies will have to diversify their interests towards composite materials. To stimulate this, increased research is needed to move towards a more efficient, greener and more flexible production of composite parts, as well as to develop a design philosophy that is specifically targeted at composite materials. This research will reduce composite part costs and further increase composites growth.

Efficient manufacturing

As the material and processing cost are higher than for metallic counterparts, we need to strive for improvements in the efficiency of production. A higher efficiency can be achieved by process automation and faster process technology.

Small details that are, at present, uncontrollable may have a large influence on the quality of a final product. To resolve this, a high level of robustness of the production processes is required, which is currently not yet the case for some processes e.g. RTM. Thus, the composites industry has reached the point where it is transitioning from 'manual processes' to 'automation', an evolution similar to what took place in the metals industry in the beginning of the 20th century. Over the coming decades, the composites world will undergo a major metamorphosis, as automation and robotics will be increasingly implemented in this field. This transition is currently underway in the automotive and the aerospace sector.
Improved efficiency may also come from the implementation of 'hybrid concepts', where products are multifunctional, based on multiple materials in a single part, or multiple production techniques in a single production step. An example of a hybrid production technique is the combination of thermoforming and injection moulding of thermoplastic composite parts.

Green composites

Aside from improving efficiency in composite production, life cycle assessment aspects such as recyclability and ecological impact will become more and more important in the coming years. Many of the processes and materials available today are considered not sustainable or not eco-friendly and have a high environmental impact. Developing new, 'greener' production processes and bio-based materials, or altering the existing processes and materials to obtain a 'clean' composite technology is a major challenge.

Design

As has been the case for years, we are still faced with the 'black aluminium' design philosophy, where designers start from a metal design and try to apply composite materials instead. We need to shift perspective from 'producing a familiar part using composites' to 'designing a light (composite) solution', that incorporates the advantages of integrated (hybrid) structures and different joining techniques. Despite all the research efforts, such as the Groups work on nano-, micro- and meso-mechanics, there is still little progress in this field. Specifically targeted workshops or trainings on this subject may help to support the 'out of the box' thinking that is required to design parts or components that can utilize the full potential of composite materials.

Foams and cores

Worth mentioning is the innovative use of sandwich foams and core materials. Foams are commonly used in a variety of (composite) applications, but only in rare cases are they specifically designed for an explicit application.

Recent developments in the group have shown that a targeted design of foams, like hybrid foams, shape memory foams and anisotropic foam for use in bicycle helmets and sandwich cores, can make significant contributions to the properties and possibilities of a part, and should therefore not be neglected. Another example is the development of a continuous production process for relatively inexpensive honeycomb core materials by the KU Leuven-spin-off company, Econcore, which opens the door to lightweight, high quality, and lower cost sandwich panels and parts.

Industrial relations

In our neighbouring countries, a clustering of composite-related businesses is taking place. Examples are the German clusters CFK-Valley Stade and Carbon Composite, or the French clusters PPE and Technocampus EMC². In Flanders, no such clustering exists at the moment. Building further upon earlier Group initiatives like Composites-On-Tour and the Technological Advisory Service, this is where the Sirris Leuven-Gent Composites Lab (SLC-Lab) can play a role.

SLC-lab is the result of an exceptional joint-venture initiative between Sirris and KU Leuven/U Gent, as was described in chapter 3. It is a 'hub' for the co-engineering of composite products through bi- or trilateral cooperation, as well as collective research with material producers, composite processers, designers and end users. Due to its unique collaborative nature, instead of competing with universities or companies, the SLC-Lab can unite partners and equipment, and bring the results and state-of-the-art production technology closer to the companies.

A good example of this is the recently started 'Generation Composite' project, which demonstrates key enabling technologies for fast, green and more flexible composite production. Another step towards a stronger, mutually beneficial link between academic research and industry is the recent integration of the university colleges with their strong industrial background into the KU Leuven association.

The demonstrator of the Generation Composite project. The demonstrator - a futuristic trailer, which doubles as a mobile exhibition space - unifies current target industries (e.g. transportation) and future target groups like the building industry and designers and architects. Once opened, the demonstrator shows its own realization by means of didactical material, movies and data sheets. This way, the key technologies can not only be shown, but also experienced.

TEXTILE COMPOSITES

The future of fibre reinforced composites in general, and textile composites in particular, seems bright. Four industrial branches – aeronautic, automotive, sporting goods and wind energy – are now major users of composites, and their demands will shape composites material science for decades ahead.

With the Airbus-380, Airbus-350 (soon) and Boeing-787 flying and being produced by the hundreds, the aeronautics industry has a high demand for further materials, manufacturing and quality control improvement.

All leading car manufacturers develop concept solutions of composites cars, with several of them already on the roads or expected there shortly. The specific price requirements and recyclability regulations of the car industry shape the research directions in somewhat different ways than in aeronautics.

The demands of wind energy for composites are extreme, both in production volumes and in material performance. Turbine blades of 90 meters, composed fully of composite materials need to run for 25 years in extreme, off-shore conditions at the same time, meeting the competitive cost limits of the energy market.

And finally, the sporting goods industry has become almost a 'traditional' user of composites, both because they allow for weight reduction and hence reduce the energy consumption by the athletes (in cycling,...) and they improve the control and efficiency (in skiing, tennis,...). Sporting goods have always been, and will remain, an ideal testing ground for new composites concepts, because the consumer demands them and the developers are not hindered by too many regulations.

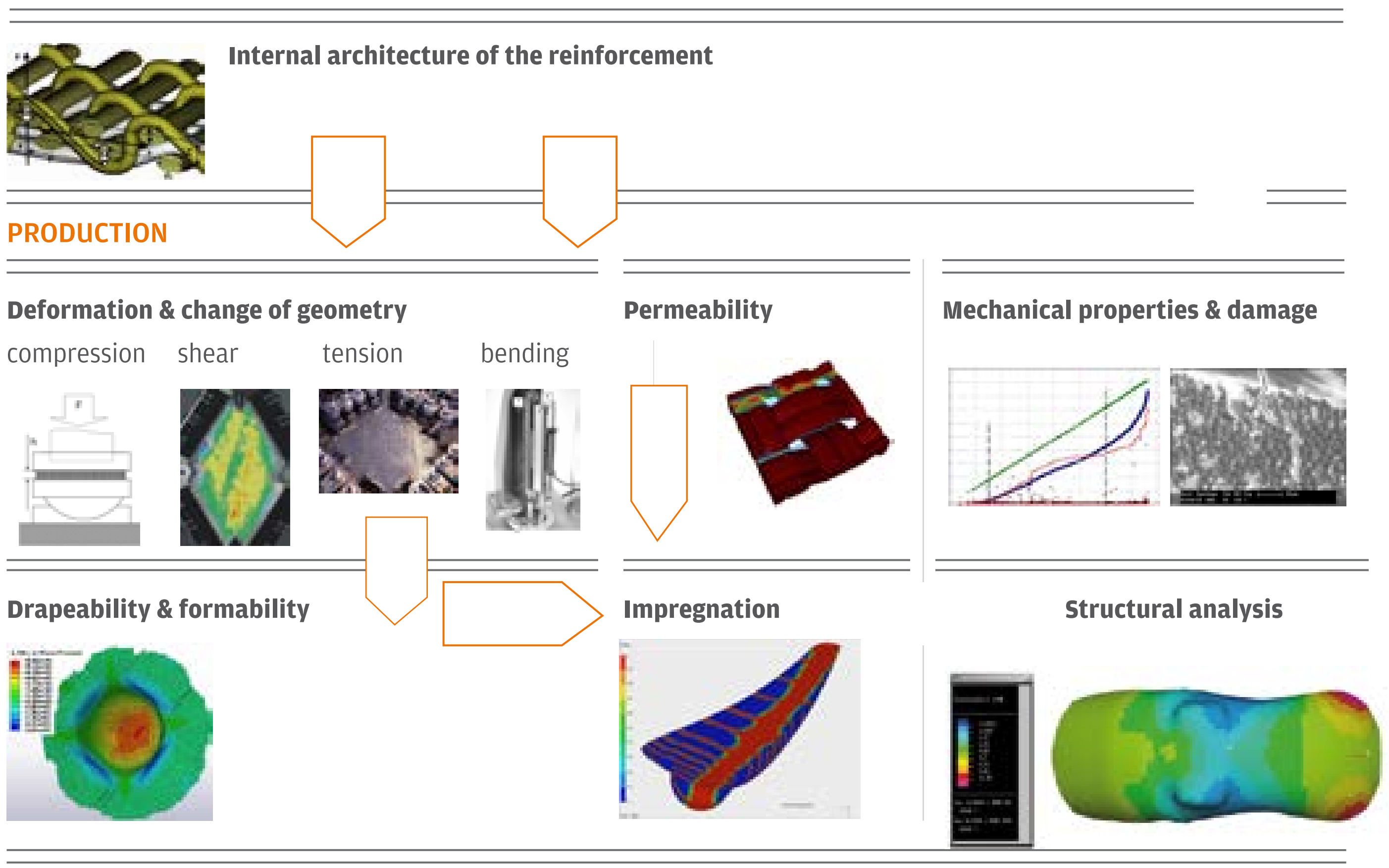
All these applications are, to a large extent, textile composites, preferably out-of-autoclave.

There exists a strong industrial demand for adequate predictive models and simulation tools, for the design of composite materials and composite parts, which are experimentally validated and based on physically sound theoretical principles. The demand is driven by the desire to resolve the conflict between the cost reduction and performance improvement of specifically designed composite parts, and the extreme cost associated with producing the samples needed for extensive physical testing in the current iterative design processes. The main industries providing this "pull" are the same aeronautic, automotive, sports and wind energy companies.

Not only end product manufacturers are pulling for increased modelling initiatives. It is also supported by the strong need for scientific understanding and predictive modelling of the behaviour of the individual constituents and their properties within a composite. Several industrial sectors are involved in this search for fundamental understanding and modelling: the chemical and materials industry (matrices and nano-reinforcements), the fibre manufacturers (carbon, glass, natural fibres) and technical textile industry (playing an important part in "resurrecting" the traditional textile industries in industrial countries).

This "industrial pull" is then also combined with an "academic push" of fundamental research, which focuses on nano-engineering, hybridization, optimisation of the reinforcement architecture and further developing the mechanics of heterogeneous media towards hierarchical multi-scale materials. In parallel, there is an important "push" from the community working on the development of numerical methods and the software industry.

Integrated design tool: textile composites



On the shorter term of the current decade, the "meso- and macro-scale" research direction in the Composite Materials Group at KU Leuven aims at reaching the following goals:

- Modelling of textile structures: "push button" software tools for the transformation of µCT images of textile composites into geometrical models and finally into finite element meshes
- Modelling of damage: validated software tools for damage prediction in textile and random fibre composites in quasi-static and fatigue loading, with an effective link between micro-, meso- and macro-simulations
- Modelling of manufacturing: validated software tools for the deformability and permeability of textile reinforcements, also with an effective link between meso- and macro-simulations
- Experimental techniques: in-situ damage observation, including microscopy, optical methods and µCT; advancing towards standardisation of measurements of deformability, formability and permeability in the framework of international benchmark exercises
- Variability: further experimental studies of stochastic effects in different types of textile composites, with special attention to natural fibre reinforcements (due to their high variability) and to carbon fibre textiles (due to the high quality requirements of the aeronautic industry)

BIO-BASED COMPOSITES

With the further rise of the bio-based economy, it is expected that the research on natural fibres and bio-polymers, to realize fully bio-composite materials, will further accelerate in the next decade. Obviously, many trends have already been set in the current research programs, but important advances are especially expected in five main following areas.

Natural fibres with improved mechanical properties, including strongly improved moisture resistance

For this, an in-depth understanding of natural fibre morphology and its relation to fibre mechanical properties is needed for various important natural fibres like flax, hemp and bamboo. Furthermore, the link between natural fibre properties and composite mechanical properties including static as well as dynamic properties like fatigue and impact needs to be established. Remedies to significantly improve the off-axis mechanical properties of natural fibres (targeting a factor 2 improvement) need to be developed, e.g. by improvement of the adhesion between elementary fibres. It is expected that natural fibres will be selected with improved properties thanks to breeding programs based on genetic screening and based on the above knowledge.

One of the most important goals remains to develop an in-depth understanding of the moisture sensitivity of natural fibres and their composites, which is linked to the fibre microstructure, and to develop some clear methods to reduce moisture absorption by more than 50%. Other new ideas may be explored, like the further development of regenerated cellulose fibres, including possible avenues to restore the natural cellulose-1 crystal structure.

Delivery of a tailor-made level of fibre-matrix adhesion

Comprehensive physical-chemical-micromechanical characterization is needed to improve and control the fibre-matrix adhesion in any natural fibre-polymer matrix composite, based on knowledge of surface energy components and chemical adhesion mechanisms. As a further benefit, this will also lead to increased composite moisture resistance through improvement of the fibre-matrix interfacial adhesion.

Breakthroughs in the processing of discontinuous natural fibres

One particular goal at KU Leuven over the next few years is to finalise the development of continuous, technical bamboo fibre prepreg tape with various thermoplastic and thermoset matrices.
Research on bio-fibres at the sub-technical fibre level, e.g. based on elementary fibres or nano-fibres should lead for example to meaningful applications of nano-cellulose material. Breakthroughs in dispersion quality by the understanding and manipulating physical-chemical parameters are expected. Another idea for the future is the development of short fibre composites based on elementary fibres with high aspect ratio.

Availability of credible bio-based matrix systems

In the nearer future, it is expected that various natural fibre-thermoplastic biopolymer matrix composites will be realised with controlled bio-degradability. A bottleneck is still the development of good quality bio-resins which will replace synthetic resins to deliver fully bio-based thermoset composites. A particular goal at KU Leuven is the development of high-performance natural fibre composites with a gluten bio-polymer matrix.

Development of hybrid natural fibre composite systems

Delivery of tailor-made natural fibre composite properties will be facilitated by the development of hybrid fibre composite systems. The target is to achieve fully natural fibre, hybrid composites, based on a solid understanding of how hybridization works.

It is finally expected that in the near future Life Cycle Analysis (LCA) will really be used as a standard and reliable tool to assess the environmental credibility of bio-composites.

NANO-ENGINEERED COMPOSITES

To design materials with yet unseen levels of toughness and strength, one must understand how the structure of a material on the nano-scale influences its behavior on the macro-scale. Future breakthroughs may be dependent on our willingness to evaluate concepts that have been around for a long time and to develop a new view of composite design. There are not only technological challenges in making nano-engineered composites but also poor understanding of how to intelligently combine reinforcements of different scales. The main questions asked today are:

How to transfer the superior mechanical properties of nano-reinforcements to composite toughness improvement on the macro-scale? One may appreciate that the wall of a carbon nanotube has a stiffness of 1TPa, but what really counts is the effect it has on the composite properties required in the design criteria of a structure. For an aircraft, such a property is the residual compressive strength after impact. The positive effect of nano-reinforcements on this property has not yet been proven.

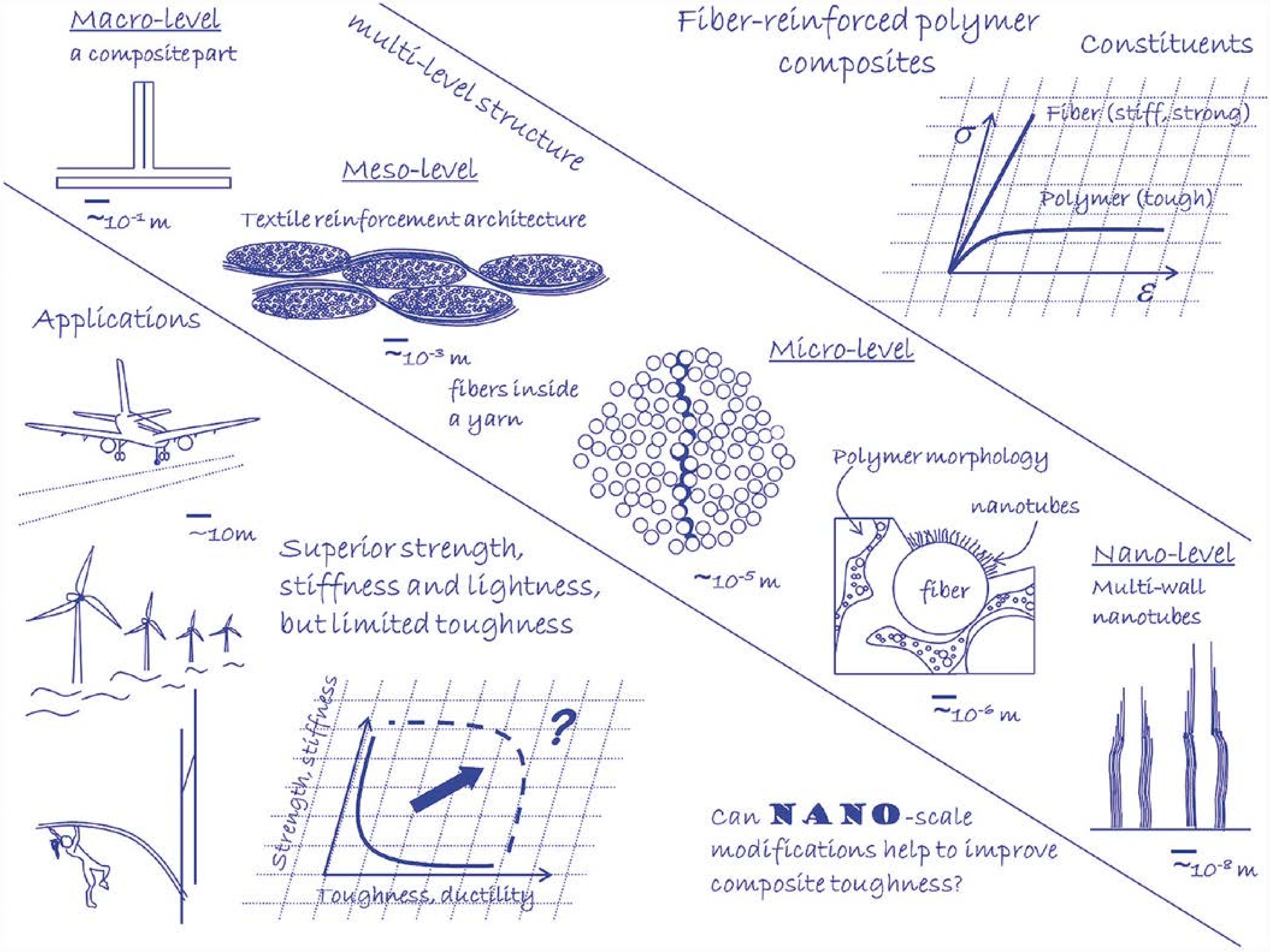
How to achieve a breakthrough (as opposed to incremental) improvement in toughness? Only significant improvements can conceptually change the way composite structures are designed today. To make a real difference, one must strive for improvement in an order of magnitude (for example, from strain to failure of 2% to 20%)

How to achieve this breakthrough improvement in toughness without sacrifice of other mechanical properties, particularly if they are governed by competing mechanisms? Composite toughness and ductility are usually coupled with its stiffness and strength. This means that these properties can only be improved at the expense of each other. Other types of materials including metals and polymers have the same limitation, thus indicating the universal nature of this problem.
Answers to these questions are hidden in design principles of naturally occurring composites. The latter exhibit properties and functionalities that are beyond those that can be achieved through a simple combination of different constituents. These properties are born from a synergy of all hierarchical levels working in unison. This is quite a different vision from the one exercised in man-made composites, which combine different constituents to benefit from their *individual* properties. It is time to make a leap forward.

In the Composite Materials Group at KU Leuven we are looking forward to advance the current state of the art by creating new fundamental knowledge in the following areas:

- Spatially resolved structural organization on the micro and nano-scale (with controlled localization, alignment, concentration, connectivity and gradients);
- Novel processing routes for composites with hierarchical and nature-inspired structures; new paradigms for creating interdependent nano- and microstructures;
- Treatments of nano- and micro-scale reinforcements to optimize their compatibility with polymer matrices and to direct self-assembly; characterization of a material's structural formation during composite processing;
- Advanced *in-situ* characterization of damage development on different scales (particularly on the micro- scale);
- Understanding of the mechanisms leading to distributed damage onset and development, ultimately resulting in the successful control of failure mechanisms through control of the material's structure;
- Multi-scale models to predict optimal structures for toughness performance; understanding of the overall structure/toughness relationships.

Teamwork at the Composite Materials Group, featuring from left to right Sergey (Russia), Eduardo(Columbia), Tom (Belgium), Jochen (Germany), Thanh (Vietnam)


Macro-level
a composite part
~10⁻¹ m
multi-level structure
Fiber-reinforced polymer composites
Constituents
σ
Fiber (stiff, strong)
Polymer (tough)
ε
Meso-level
Textile reinforcement architecture
~10⁻³ m
Applications
Micro-level
fibers inside a yarn
~10⁻⁵ m
Polymer morphology
nanotubes
fiber
~10⁻⁶ m
Nano-level
Multi-wall nanotubes
~10⁻⁸ m
~10m
Superior strength, stiffness and lightness, but limited toughness
Strength, stiffness
Toughness, ductility
?
Can NANO-scale modifications help to improve composite toughness?

BUILDING NETWORKS & NURTURING FRIENDSHIPS

Networking is extremely important for a research group. Embedding itself into the worldwide scientific community, a research group achieves a synergetic effect, cross-fertilising, amplifying and multiplying ideas and results. The old adage "If you share an apple with a friend, you both have half an apple – if you share an idea, you both have it whole" is more than true in science. Science-metry, a discipline that emerged in 1950s and resulted in such instruments as Science Citation Index, has introduced the idea of an "invisible lab," a community of scientists who may never even meet, but who work in close contact via means of scientific communication such as journal papers or conferences. Nowadays, use of the internet facilitates this networking, which can happen instantly, on the "click".

It is important to realise that networking does not happen spontaneously, even if you attend a dozen conferences per year. You have to consciously utilise formal and – perhaps more importantly – informal ways of establishing links with your peers to create these "invisible labs," even if there is no financial framework behind them, and even if you do this just because this is a natural *modus vivendi* of us scientists as a species. Of course, no harm is done if the collaboration is funded by some generous public body or interested industry! Since the very beginning, the Composite Materials Group nurtured professional collaborations on the personal level, and encouraged a "metamorphosis" of these personal relationships into institutional collaborations. This is clearly seen in the patterns of our different networking types: a country targeted network, grown from a close individual collaboration, participation in and organisation of conferences, creation and participation in multidisciplinary platforms, teaching abroad and many others described below.

FROM PERSONAL EXCHANGES TO INSTITUTIONAL COLLABORATIONS: THE WHOLE WORLD IN LEUVEN

Starting in the mid-nineties, the Composite Materials Group became truly international, illustrating a distinct feature of the group in the new millennium. People of more than ten nationalities, from four continents, work together in Leuven at any moment of time. Several countries are of special importance for the Composite Materials Group, with long term collaboration resulting in intensive exchange of people and ideas. The European and world-wide network, established via participation in joint consortia or organisation of conferences, is much wider.

JAPAN

The interactions with Japan were started through the participation of Ignaas at conferences on interfaces, as well as the presence of Japanese textile composite researchers at the first TEXCOMP-conferences in Leuven. The discussions with Prof. Tanimoto (Shonan Institute of Technology) on interfaces led to the research stay of Torhu Morii in Leuven (1994-1995), and similar interactions with Prof. Hiroyuki Hamada (Kyoto Institute of Technology) on interfaces and textile composites resulted in the stay in Leuven of Asami Nakai, now a professor at Gifu University.

For several decades already, there had been a strong collaboration (on shape memory alloys) between Kansai University and KU Leuven. In the framework of this collaboration, Prof. Mitsukazu Ochi stayed for a sabbatical in Leuven in 1994, and Ignaas went to Kansai University for one month in 1999, very much enjoying the daily life in Japan.

All of this collaboration created extremely strong ties with Japan. The interactions and exchanges are too numerous to mention them all: Prof. Mitsukazu Ochi (Kansai University), Prof. Masaru Zako (Osaka University), Prof. Torhu Morii (Shonan Inst. of Technology), Prof. Asami Nakai (Gifu University), Prof. Kazuaki Nishiyabu (Kinki University) and Prof. Satoshi Hanaki (Hyogo University) , all have spent a sabbatical in Leuven by Multiple exchange visits have been organised with other universities like Tokyo University (Prof. Jun Takahashi), Nagoya University (Prof. Takashi Ishikawa), and Kanazawa Insitute of Technology (Profs. Kimpara and Kimura)… .

Since the mid 90's, either Ignaas Verpoest or Stepan Lomov have visited Japan every year. Four collaborations have gained more importance over the past ten years.

Prof. Mitsukazu Ochi and Prof. Ignaas Verpoest during his stay at Kansai University

Stepan Lomov and Mazaru Zako in Venice

In Osaka University, 2013: T.Tsujikami, N. and M. Sugahara, S. Hanaki, M. Zako, S.V. Lomov, T. Kurashiki – all Osaka colleagues visited Leuven at different times

The Composite Materials Group participates in a research consortium of the Japanese industry, led by Prof. Masaru Zako and later by Prof. Tetsusei Kurashki (Osaka University), focused on textile composites modelling. The most important result of this collaboration is the establishment of a "road map" for finite element modelling of textile composites which includes a geometrical pre-processor, a geometry correction and meshing, the setting of periodic boundary conditions and a finite element solver with damage modelling capabilities. The "road map" is implemented in software tools, simulations models and software jointly developed by the "Zako/Kurashiki-lab" in Osaka and the Composite Materials Group in Leuven.

Several visits of Ignaas to Tokyo University and of Prof. Takahashi to KU Leuven have led to a better understanding of the environmental impact of carbon fibres, mainly in automotive applications. Prof. Takahashi also coordinated the most recent large project on carbon fibres, funded by the Japanese government, which inspired the Composite Materials Group at KU Leuven to explore the potential of a new type of carbon fibre reinforcement for mass production applications.

Informed on KU Leuven's role in the TECABS-project, Toyota established a close collaboration with the Composite Materials Group in parallel with their involvement in important government funded projects on the use of carbon fibre composites in Japan. A project on the fatigue behaviour of a novel type of carbon fibre prepreg was performed, funding the PhD-research of Katleen Vallons (2005-2009), who also spent a month in Toyota-city. Recently, interactions have resumed and a new collaboration project is in preparation in the framework of the Flemish SIM-projects.

The Japanese collaboration was "crowned" in 2012 by establishing the Toray Chair for Composites Research in the Department MTM, held by Prof. Ignaas Verpoest. In the text box, the history behind, and the importance of, the Toray Chair is explained (excerpted from a joint press release). Since its existence, many scientific and technical meetings have increased the interaction between Toray and KU Leuven. Specific studies have been started, and new projects are in preparation.

VIETNAM

The Vietnamese links to the Composite Materials Group started in 2000 with Truong Chi Thanh who did his Masters and PhD in KU Leuven, spending almost seven years in total in Leuven. Now, back in Vietnam, Dr. Truong Chi Thanh coordinates the collaborations with Can Tho University and our ties with Vietnam have been strengthened year by year, supported by the Belgian Federal Science Policy Office (BELSPO) and the Flemish Government (through its VLIR-program). The Composite Materials Group, with strong help from Jo Mariën, helped establish a composites lab at Can Tho University.

An interesting aspect of the collaboration with Vietnam is the difference in perspective from Belgium where the research is driven by the demands of the European composites community which are not always the same topics important for the Vietnamese society. The PhD research of Truong Chi Thanh was on carbon non-crimp fabric composites in the framework of EU project TECABS. Now the focus of collaboration lies on natural fibre composites (coconut, bamboo) which are the subject of PhD research of Ngoc Tran Le Quan, and on bio-based polymers (PhD of Nhan Vo Hong).

The alignment of research to local economic needs is a characteristic feature of the natural fibre research in the Composite Materials Group. PhD researchers from Columbia, Lina Osorio Serna and Eduardo Trujillo de Los Rios, together with Carlos Fuentes from Peru study bamboo fibres, Rashnal Hossain from Bangladesh explored the potential of jute fibres, and earlier in his PhD, Paul Wambua from Kenia proposed protective anti-landmine materials also based on local natural fibres.

Thanh, Ignaas, Tri and Ngoc in front of the Materials Engineering Department at Cantho University in 2008
(below) The natural fibre team in the Composite Materials Group : Lina, Dieter, Carlos, Farida, Eduardo, Ngoc, Nhan

USA

The collaboration with the USA began at the very beginning of the Composite Materials Group: Ignaas Verpoest attended the composite materials workshop of Profs. Steve Tsai and George Springer (Stanford University) at DLR in Germany, and subsequently invited them to teach similar workshops in Leuven over the next several years (see also Chapter 1). Once the composites research in Leuven had been established, and the group had grown to 5 people, Ignaas spent eight months (1986-1987) as postdoctoral researcher at the Aero/Astro Department at Stanford University working on moisture absorption in aramid fibre composites. Some of George Springer's and Steve Tsai's PhD-students at that time, became future partners in European and international collaboration projects (Antonio Miravete at University of Zaragoza, Lars Berglund at KTH-Stockholm, Larry Lessard at McGill in Canada).

Attending conferences in America during that sabbatical, Ignaas also met Profs. Tsou Wei Chou (University of Delaware) and Frank Ko (Drexel University), and found joint interest in textile composites. This would be the start of a fruitful collaboration, resulting in many future endeavours, including the creation of the TEXCOMP conferences and the sabbatical stay of Frank Ko in Leuven. More recently, prof. Ko inspired a student at Drexel, Kelly Vandenbosche, to start a PhD at KU Leuven.

Prof. Richard Parnas of the National Bureau of Standards (now in the University of Connecticut) during his sabbatical in Leuven in 2000-2001 significantly influenced the future work of the Composite Materials Group in many fields such as permeability measurement and prediction as well as the micro-CT investigation of the internal structure of textile reinforcements. His ideas of standardisation of permeability measurements were the basis for initiating international benchmarking permeability exercises in the second half of the 2000s.

Also in the early 2000s, a long and fruitful collaboration with Dr Alex Bogdanovich of 3Tex (now in the North Carolina State University) was started. This collaboration revolved around 3D woven reinforcements, which were studied in detail for their architecture, behaviour during composites processing, and their mechanical properties in quasi-static and fatigue loading, including damage development. Via the Composite Materials Group, other international collaborators were included in this work –
Dr Mehmet Karahan of Uludag University in Turkey and Prof. Valter Carvelli in Politecnico di Milano. In addition to this specifically focused research, other interactions, discussions and sometimes disagreements with Dr Bogdanovich were very fruitful in developing a nuanced understanding of the complex phenomena driving the mechanical behaviour of textile composites. The list of joint publications of the Composite Materials Group and Dr Bogdanovich includes 21 papers.

In the last decade, new USA collaborations have also been started and old ones strengthened. The collaboration with Dr. Brian Cox (Teledyne) dates from the 80s, when Ignaas Verpoest and Jan Ivens visited him in California, and Philip Vandeurzen, a PhD student of the Composite Materials Group, had a research visit to USA. In 2010 a bright idea of Dr Brian Cox on the mathematical formulation of a textile reinforcement variability attracted attention of Stepan Lomov. This led to a research visit to California by Andy Vanaerschot, a PhD student supervised by Prof. Dirk Vandepitte and Stepan Lomov. This collaboration resulted in the advancement and transfer of the concept, originally applied to ceramic composites, to the field of fibre reinforced plastics.

Yet another successful collaboration in the United States, with Prof. Brian Wardle of MIT, was instigated by mutual interest in understanding the problems arising in the manufacturing of nano-engineered fibre reinforced composites.

RUSSIA

With Stepan Lomov settled in Leuven, the Composite Materials Group received a strong influx of Russian PhD students and post-docs, with connections to composites research groups in St-Petersburg and Perm. These were Dr. Eugene Belov, Dr. Vitaly Koissin and Dr. Sergey Ivanov, PhD students Sergey Kondratiev, Dmitry Ivanov, Oksana Shishkina, Valentin Romanov, Svetlana Orlova and Ilya Straumit, visiting researchers Dmitry Mikhaluk and Dmitry Klimshin. In 2007, Stepan Lomov organised an international symposium in St-Petersburg on finite element modelling of textile composites.

In 2013, KU Leuven entered an international consortium "Advanced Materials and Structures" in support of Russian research centre and new university, the Skolkovo Institute of Technology (SkolTech). The consortium includes leading world centres of composites research, such as MIT, South Carolina State University and Dayton University in USA, Delft and Berlin Universities in Europe, TsAGI and institutes of Russian Academy of Science. When started, the five year research program of the consortium, funded by the Russian Government, will provide a broad framework for research in composite mechanics and a further influx of Russian researchers and students in the Department MTM. Russophones have a good chance to remain the second largest language community in the Composite Materials Group.

SWITZERLAND

Since Stepan Lomov had joined the Composite Materials group as senior postdoctoral researcher, and the Composite Materials Group had grown to a team of 15 researchers, Ignaas Verpoest found that the time was right to plan a second sabbatical leave. Contacts with the Ecole Polytechnique Fédérale de Lausanne (EPFL) had already been initiated during the sabbatical stay in EPFL of Prof. Ludo Froyen, a colleague at the MTM. The enthusiasm and creativity of the team of Prof. Jan-Anders Manson, Dr . Veronique Michaud, Pierre-Etienne Bourban, Yves Leterrier had already impressed Ignaas a lot, and would lead to the inclusion of EPFL in the famous TECABS-project as well as to Ignaas's sabbatical stay in EPFL in 1999-2000.

The contribution of Prof. Jan-Anders Manson and Dr. Veronique Michaud to the TECABS-project was focused, among other topics, on manufacturing and life cycle analysis of composites. During his sabbatical, Ignaas found more areas of common interest like interfaces and bio-based composites. This was a perfect basis for further interactions, and CMG and the EPFL composites group would be each-others hosts/guests three times in the following years, combining scientific discussions with snow adventures in Alps and Belgian beer testing.

Several formal collaborations would follow, including the project with Bekaert on steel wire composites, and the HIVOCOMP, where KU Leuven and EPFL compose the backbone of the project. The collaboration on life cycle analysis has recently been extended to Prof. Karel Van Acker (Leuven Material Research Centre).

Ignaas Verpoest has several times been a member of PhD committees at EPFL. And most recently, Ignaas spent a second, three-month, sabbatical at EPFL (2012).

FRANCE

During the early days, the Composite Materials Group collaborated with Ecole des Mines deParis (Prof. Tony Bunsell), in the framework of EUPOCO, the first European Master degree in Polymer and Composites Engineering. Much later, the late Prof. Alain Vautrin (Ecole des Mines St-Etienne) spent a sabbatical in Leuven in 2002. His expertise helped the Composite Materials Group to establish optical experimental mechanics capabilities in the mechanical testing lab, and his open personality enhanced the "work-and-have-fun" atmosphere in the group. The collaboration continued further, resulting in several joint papers.

Optical measurements of textile deformations during the forming of a composite reinforcement were also a topic of collaboration with Prof. Philippe Boisse (INSA Lyon). The collaboration continued toward finite element modelling of textile deformation – Prof. Boisse is a leading specialist in this field, and the Composite Materials Group benefited from close interactions with him and his colleagues in the framework of the ESAFORM conference, the international benchmark exercise on formability, and in direct collaboration. Algorithms for finite element modelling of fabric deformation, provided to the group by Prof. Boisse, served as a starting point in PhD research of An Willems and Kristof Vanclooster.

Interactions with ONERA, the French research centre for aeronautics, were first started by Dr Fabrice Boust and continued with the work of his PhD student Bertrand Laine, who spent several months in Leuven during his PhD studies. The WiseTex software of the Composite Materials Group was integrated with flow calculations of ONERA. Bertrand Laine and Stepan Lomov initiated the first international permeability benchmark which demonstrated a pressing need for standardisation of preform permeability measurements for reliable input into simulations of liquid moulding composite processing. The collaborations with the French aeronautics industry continued with Snecma (SAFRAN Group, Dr Dominique Coupe, Dr Bruno Dambrine, Dr David Marshall, and PhD student Guillaume Perie), with the development of methods for the prediction of the mechanical properties of 3D woven turbine fan blades.

The Composite Materials Group is also engaged in long-term collaborations with the ESI Group (Dr Patrick de Luca), a French-German software company, which holds a leading position in the development of specialised software tools for the simulation of composite production and performance. The collaboration continued through asuccession of European projects (TECABS, ITOOL, INFUCOMP, HIVOCOMP). The WiseTex textile modeller modules are incorporated in the SYSPLY software from the ESI Group.

Japanese composite producer Toray endows chair for fundamental research at KU Leuven

Since 2012, Toray, the Japan-based multinational and the world's largest producer of carbon fibre, is investing in a chair for fundamental research in composite materials for Professor Ignaas Verpoest of the Department of Metallurgy and Materials Engineering. "We have been looking for collaboration partners in Europe. Professor Verpoest is a pioneer and a 'legend' in the composite material field in Europe," said Yukichi Deguchi, Toray's vice president for research and development."A member of our lab worked as a researcher in Leuven for two years and built a strong relationship with Professor Verpoest and his team. In November 2011, I met with Professor Verpoest and we agreed to begin a long-term collaboration." The format chosen for this collaboration was a three-year endowed chair with the possibility of extension.

The budget will go toward fundamental research into the further refinement of composite materials based on carbon and other fibres. Akihiko Kitano, general manager of Toray's Composite Materials Research Laboratory: "We are the market leader in carbon fibre technology based on polyacrylonitrile fibres (PAN), which we put to use when developing composites for the primary structures of aircraft. Together with Professor Verpoest, we want to increase our understanding of these materials and build new composites for use in lighter, safer aircraft." The researchers utilise advanced experimental techniques and software to predict the behaviour of composites. In a press conference, Prof. Ignaas Verpoest stated: "The Toray endowed chair is not only important for financial reasons; it also enhances the international reputation of our research group. It really speaks volumes that this Japanese heavyweight chose our university as the anchor for its cooperation with the European academic world."

Dr. Yukichi Deguchi, vice-president of Toray, Prof. Karen Maex, vicerector of KU Leuven and Prof. Ignaas Verpoest signing the endowed chair agreement. *(picture: Rob Stevens)*

GERMANY

In the first chapter of this book, it was already explained how Ignaas Verpoest and Klaus Drechsler met at an ESA-conference at ESTEC-Noordwijk, where they both presented the same concept of using 3D fabrics for composite sandwich structures without having talked to each other ever before. This was the start of a long friendship of almost 30 years, and collaboration in the framework of different European projects SAMPE-Europe. Wherever Klaus moved (MBB, EADS, Daimler-Chrysler, University of Stuttgart and finally the Technical University of Munich), he succeeded in establishing a collaborative project with KU Leuven!

Around the same time, the collaborations started with Profs. Karl Schulte (TU Hamburg-Harburg) and Edith Mäder (TU Dresden), in the framework of several EU-funded projects, and with dr. Piet Peters at DLR.

Collaboration with the ESI Group in Germany involves Prof. Anthony Pickett (University of Stuttgart), who strongly influenced the work in the Composite Materials Group related to finite element modelling of textile composites. ITA in Aachen (Prof. Thomas Gries) is a long-term partner of the Group in textile research. In recent years, strong links have been built with the TU Munich (Dr. Joerg Cichosz, PhD student Christoph Hahn) in integrating our geometrical textile modeller, WiseTex, with user software tools. With Dr. Gerhard Kalinka from BAM (Federal Institute for Materials Research and Testing) in Berlin the Group collaborated on the characterization of nano-engineered interfaces in composites.

ITALY

Italian researchers and institutions played an important role at several stages of the development of the Composite Materials Group of KU Leuven. Without the enthusiastic belief of the Fantino brothers and their company Metalleido, the concept of the composite sandwich panels based on 3D fabrics would never have evolved into a commercial product.
Later on, Prof. Ignazio Crivelli-Visconti (University of Naples) was an integral part of the realisation of the first Composites-on-Tour project, enabling us to travel down to Napoli with the mobile exhibition in the composite trailer.

Since 2002, an intensive collaboration was built with Politecnico di Milano (Profs. Carlo Poggi and Valter Carvelli). The collaboration exploits the possibilities offered by the Erasmus exchange program of the European Union. Stepan Lomov has delivered three modular doctoral courses in Milan on textile composites and mechanics of heterogeneous media. Master and PhD students of Valter Carvelli come to Leuven almost every year, and in 2013, the first Master student from Leuven went to Milan. The collaboration concentrates on 3D textile reinforcements, and has resulted in 20 joint publications.

Ignaas Verpoest during the inaugural lecture of the Francqui Chair at UCL

Valter Carvelli, Stepan Lomov and Carlo Poggi in Milan, 2001

UNITED KINGDOM

From the very beginning, the Composite Materials Group interacted with researchers from British universities. In the first European project on "Effects of Defects" profs. Antony Kelly and Mike Bader (University of Surrey) participated. When lecturer Frank Jones moved from there to become a professor at Sheffield University, the collaboration on interfaces in composites was intensified, not only in European projects but also in the organisation of the series of conferences on interfaces IPCM (Interfacial Phenomena in Composite Materials).

Caroline Baillie, at that time a PhD-student on interfaces at Surrey University, moved to Imperial College and became one of the inspiring collaborators in the Composites-on-Tour adventure. Earlier on, Prof. Frank Matthews at Imperial College was for a decade a strong partner in the master program EUPOCO. More recently, the collaboration with Imperial College has been intensified by interactions in the area of nano-engineered composites (Prof. Alexander Bismarck, Prof. Milo Shaffer and Dr. Emile Greenhalgh). The London connection was further extended by collaborations with Profs. Ton Peijs and Paul Hogg at Queen Mary. After his PhD at KU Leuven, Dmitry Ivanov moved to Bristol University and was a catalyst for further collaborations with the research group of Prof. Michael Wisnom

Enjoying walking on the Chinese Wall after ICCM-13 In Beijing (2001): Anoush Poursartip (University of British Columbia), Caroline Baillie, Ignaas Verpoest, Larry Lessard and wife (Mc Gill University)

THE NETHERLANDS

Being our closest neighbour and speaking the same language, collaborations with Dutch universities are evident! The late prof. Theo de Jong and prof. Adriaan Beukers (Technical University of Delft) were from the very beginning strongly involved in EUPOCO, and Adriaan has been teaching in Leuven for more than 20 years. He also was very committed to the first Composites-on-Tour, inspiring designers with his original views. Another joint work with TU Delft, Prof. Zafer Gurdal, in AUTOW and CANAL EU projects, was modelling of mechanical properties of composites manufactured with an automatic tape placement technique.
The collaboration with prof. Remko Akkerman (University of Twente) focusses on process modelling of composites, namely permeability and drapability of textiles. Richard Loendersloot performed, as a visiting PhD-student, extensive studies of deformability and permeability of non-crimp fabrics.

BELGIUM

The project on composite tennis rackets in the early 80's, the very start of composites research at KU Leuven, was a joint project with the late prof. Robert Dechaene at Ghent University. His PhD-student at that time, Joris Degrieck, became his successor, and has always been a reliable and enthusiastic 'compagnon de route' in promoting composites in Flanders. Numerous projects on the mechanical behaviour of composites have been successfully submitted to the Belgian and Flemish funding authorities. More recently, Joris and Ignaas represented their universities in the development of SIM, the 'Strategic Initiative Materials' of the Flemish government. In the SIM-projects NanoForce and M^3, Joris and his colleague Prof. Wim Van Paepegem collaborate with Stepan Lomov and Larissa Gorbatikh on modelling of steel fibre and textile based composites, and on short fibre composites, and jointly guide several PhD-students.

In the first Belgian collaborative projects, also the Free University of Brussels (VUB) played an active role, namely Prof. Patrick Dewilde and the late prof. Albert Cardon. Prof. Hugo Sol continued the collaboration, mainly focussing on NDT and processing of composites, like on permeability measurements of textile composites (PhD of Kris Hoes) and in the project with the company ASCO. In the recent SIM-programs, Prof. Danny Van Hemelrijck continues to contribute to the mechanical characterisation of composites.

Although unfortunately collaborations across the language border are not easy in the federal state of Belgium, our sister university Université Catholoque de Louvain (UCL) has always been a preferential partner. In the first decade, we enjoyed the funding of our fundamental research through one of the only remaining 'Belgian' institutions (the 'Interuniversity Attraction Poles' or IUAP's), but the collaboration really intensified via the joint organisation of the EUPOCO master degree (see Chapter 2). Prof. Roger Legras, Jacques Devaux, Roland Keunings and Francois Dupret all have been teaching for more than 15 years in the program. In return, Ignaas Verpoest was invited to teach composites in the regular materials engineering program at UCL.

The formal and informal collaborative projects (exchange of master's and PhD-students, use of each others experimental facilities,...) are too many to be mentioned all. An intense period of collaboration was the early 90s, with three former UCL-students doing research at KU Leuven (Muriel Desaeger, Bernard Goffaux and Alain Verhoyen), simultaneous with Thierry Lacroix working at UCL on interfaces. Our joint paper on micromechanical modelling of interfaces has still one of the highest number of citations of all our papers.

The collaboration is now again intensifying, with interactions on interface characterisations (Prof. Christine Dupont), mechanics of composites (Prof. Thomas Pardoen), short fibre composites (Prof. Issam Doghri) and polymer science (Prof. Jacques Devaux and Christian Bailly). As a recognition for this long and fruitful collaboration, Ignaas Verpoest was awarded in 2008 the prestigious Francqui Chair at UCL.

The first Texcomp conference at KU Leuven

INTERACTIONS VIA, AND IN, CONFERENCES

The Composite Materials Group's international network was strongly supported by participating in and organising of international conferences.
Since the first Composites-on-Tour initiative (2002), the Composite Materials Group is represented by a booth in the yearly JEC exhibition in Paris, and contributes actively to the organisation of at least one of the JEC-forums each year.

Other conferences important for the group were the SAMPE conferences in Europe, USA and Japan, and the more topical IPCM, ESAFORM, CompTest, FPCM conference series. Stepan Lomov is a member of the Scientific Committees of the latter three. Being strongly focused, these conferences are a kind of "clubs" for the worldwide composites specialists in forming, model identification and flow processes. Several international benchmark exercises were organised by these "clubs". In 2007 Stepan Lomov organised a special international symposium on finite element modelling of textiles and textile composites in his native St-Petersburg.

TEXCOMP

A very special case of a topical conference is TEXCOMP, an international conference on textile composites. It was started by the Composite Materials Group in Leuven in 1992, travelled over the world, alternating Europe – USA – Japan and back, and now its 11th edition is back in Leuven in 2013.

ICCM AND ECCM

ICCM, the International Committee on Composite Materials, was founded in 1975 on the occasion of the organisation of the very first International Conference on Composite Materials, remarkably held on two locations, Geneva and Boston (participants travelled from one place to the other!). From the very beginning, Steve Tsai played a crucial role in this organisation, trying to create a platform where scientists from all over the world could meet to exchange ideas and innovations in this new field of materials science (carbon fibres just had been introduced on the market!). Ignaas Verpoest participated for the first time at the ICCM-conference in London in 1987, and has participated since in all ICCMs (ICCM-6 London through ICCM-19 in 2013 in Montréal), except ICCM-7 in Bejing *(see box below for the story)*. In 1991, during ICCM-8 in Honolulu), Ignaas was elected as a member of the Executive Council, and as Vice-President

Marie Curie nieces and nephews

The dedication to multi-cultural cross-collaboration was enhanced by the Marie Curie Training Site programme from 2002 to 2004, coordinated by Stepan Lomov. For this programme, 13 Marie Curie Fellows - PhD students from European universities - came as visiting researchers to Leuven for six to nine months each (Quentin Oskar and Stuart McCallum, UK; David Ranz and Enrico Bernal, Spain; Richard Loendersloot, the Nederlands; Marcin Barburski, Poland; Matteo Vettori, Italy; Tzvetelina Stoilova, Bulgaria; Vladimir Lukas, Tomas Mikolanda and Jan Vodolan, Czech Republic; Gabriel Furtos, Romania). Their work was organised in clusters of topics (non-crimp fabrics; finite element models of textile composites; optical measurement methods), which created micro-teams together with "regular" members of the group.
This programme led to an extraordinary situation of "human alchemy," in which strong social bonds were developed among the members from all around Europe. A good illustration and testament to this is that five Leuven colleagues travelled to Krakow for the wedding of one of the "Marie Curie nephews", Marcin Barburski. On another occasion, several group members and Marie Curie Fellows travelled down the Chusovaya River in the Ural Mountains of Russia with Dmitry Ivanov.
For the majority of the Marie Curie Fellows, the work in Leuven was well-published and constituted a substantial part of their PhD theses. Fruitful collaboration with a number of them continued in the group in subsequent years.

CMGers at Marcin's wedding in Krakow: Marcin Barburski, Anna Barburska, David Ranz Angulo, Ericka Jao Jules Nordlund, Francesca Zilioli (Matteo's wife), Matteo Vettori, Sveta Malinina (Sergey's wife), Sergey Kondratiev, Richard Loendersloot, Marleen Korte

The Executive Council at ICCM-14 in San Diego

The Executive Committee of ESCM at the ECCM in Bristol, 2000

Half of the materials researchers of KU Leuven during the MRC-start up in 2006

for Europe in 1999. During ICCM-14 in San Diego in 2003, Ignaas was elected President of ICCM (in office until 2005). It was an exciting 15 years of commitment to further the growth of ICCM, to the largest composites conference worldwide, combining high standards of quality for presentations with efficient organisation and a convivial atmosphere. In 2007, Ignaas was awarded the title of 'World Fellow and Life Long Member' of ICCM.

The story of ESCM, the European Society of Composite Materials, follows a similar path, although a little more 'tortuous!' EACM, the European Association of Composite materials, had been founded in 1985, supported by the strong composites activities in the Bordeaux-region (France). Over 13 years, EACM served the European composites community by organising (the now well established) ECCM-conferences, and by a series of other initiatives. However, when the support of the French government was drastically reduced, a new organisation had to be invented. In June 1997, a Provisional Council, chaired by Ignaas Verpoest, gathered in London to discuss the transition from EACM to the new organisation. General guidelines were agreed upon, a Provisional Executive Committee was installed, and Ignaas was elected as Provisional President. They were given the task to propose a new Constitution and Regulations, and to prepare the foundation of the new organisation. The experience in ICCM proved to be very valuable, and the Constitution for the new organisation was heavily inspired by the ICCM-constitution (elaborated under the leadership of Paul Lagacé, who had referred to the rules in power in the International Olympic Committee!).
The Constitution and Regulations of the new organisation, called ESCM, was presented for approval to the General Assembly during ECCM-8 in Naples (Italy) in June 1998, and Ignaas was elected as first president of ESCM. In 2002, ECCM-10 was organised in Belgium (Brugge), jointly with Prof. Albert Cardon (VUB) and Joris Degrieck (UGent). This was a remarkable event, as it was also the start of the European tour of the first Composites-on-Tour exhibition.

INTERDISCIPLINARY PLATFORMS

LEUVEN MRC

Collaboration across the boundaries of scientific disciplines has always been important for the Composite Materials Group at KU Leuven. Already in the mid-90s, Ignaas Verpoest was one of the co-founders of the Materials Research Centre at KU Leuven. It was an initial attempt to bring together all research groups at KU Leuven involved in materials research and technology development. It was a platform for exchanging ideas and elaborating joint research projects, for instance to acquire expensive research infrastructure (like electron microscopes). After some initially successful years, the activities decreased because contribution to the centre was purely voluntary.

At the restart in 2005, it was decided to create a better performing structure. The university and it's tech-transfer organisation, Leuven Research&Development (LRD), provided financial support for the appointment of an MRC-coordinator, whereas the working budget is, to a large extent, provided by each of the 20 participating research groups, spread over 3 faculties and 9 different departments. Ignaas Verpoest was elected chairman of LeuvenMRC and, together with Prof. Karel Van Acker, MRC-coordinator, and the MRC-steering committee, the Materials Research Centre developed into a virtual centre of interaction and collaboration between more than 60 professors and nearly 500 researchers. A large variety of materials are studied: metals and alloys, structural and functional ceramics, composites, polymers, building materials, biomaterials, functional coatings and CNTs, among others. The interactive, cross-disciplinary projects are grouped around six research lines: tailored nanoparticles, functional surfaces for microsensing and –synthesis, polymer nanocomposites, biobased polymers, sustainable inorganic materials management and multiscale engineering of metals and ceramics.
The Composite Materials Group is actively involved in several large projects, which were initiated inside the MRC-interactive platform, including the two projects on gluten-based polymers and composites, the GOA-project on carbon nanotubes in carbon fibre composites, and the EU-project Nancore on nano-reinforced foams.

SIM, THE STRATEGIC INITIATIVE ON MATERIALS IN FLANDERS

As chairman of the Leuven Materials Research Centre, Ignaas Verpoest was heavily involved in the creation of SIM, the 'Strategic Initiative Materials,' an idea launched by the Flemish industry organization Agoria. Initially, the discussions related mainly to the basic concept of SIM, and the universities (Ignaas, Karel Van Acker, coordinator MRC, Paul Vandun, director LRD and Koenraad Debackere, general manager of the university for the KU Leuven-side) convinced Agoria and the Flemish government that a 'virtual' institute with a lean management structure, leaving the university researchers in their 'natural habitat,' would be the best solution.
Results of several brainstorming sessions with representatives from industry and academia were combined with existing roadmaps to develop a master plan defining the organization and contents of the future SIM. Within the theme 'sustainable structural materials,' the program NanoForce was proposed and accepted. It was based on preliminary research on steel fibre composites with the Flemish company Bekaert *(see chapter 3)* and aimed at studying the fundamentals of these rather unusual composites.

The Transsiberian Railway to Beijing ?

In 1989, ICCM-7 was planned to be organised in Beijing. Having always dreamed of once going to Beijing by the Transsiberian Railway, Ignaas started a 'crazy' initiative. A call was launched to all PhD-students in composites in Europe, asking whether they would be interested to join the adventure. A group of 20 young researchers from all over Europe were selected, and a fund raising campaign successfully collected money to financially support them.

We would fly to Moscow, board the Transsiberian train for one week, having scientific discussions in the morning and enjoying ourselves in the afternoon. Ignaas' wife Chantal and two children, Klaas and Lien, would also join. After the conference, a short tour in China was planned before returning by plane to Europe. All the train, plane and hotel reservations were done, with the help of Liz, the wife of Tad Doxsee who was at that time a postdoctoral researcher from Stanford University at KU Leuven.

Prepayments of the rail tickets would be done on Monday, when on the first Sunday of June 1989, the students' protest on Tiananmen Square in Beijing escalated, and the army started to forcefully clear the square. At that moment, the fear that ICCM-7 would be cancelled became stronger, and the hard decision had to be made to not buy the rail tickets, and a few days later to cancel the whole adventure! ICCM-7 was transferred to Guang-zhou, a few months later than initially planned, gathering only a very small attendance...

The basic idea of SIM, namely to involve all relevant research partners in Flanders in order to create complementarity and synergy, was perfectly realized within Nanoforce, as all universities (Leuven, Gent, Brussels, Antwerp) and research institutes (VITO) were involved. It even allowed us to start a very 'risky' project, aiming at producing carbon fibres as aligned carbon nanotube bundles, nicknamed *light steel fibres*, as we hope they will combine the stiffness and toughness of steel with the lightness of carbon fibres. NanoForce would also be the start of our collaboration with LMS *(see chapter 4)*.

Ignaas Verpoest at the SIM Users Forum in Antwerp, 2012

TOPICAL NETWORKS

National and European research funding organisations have ample possibilities for the organisation of "networks" around certain scientific or technical topics, providing funds for exchange of researchers, organisation of workshops, etc...

The Composite Materials Group was a member of the OPTIMESS network for optical measurement techniques for structures and systems, funded by FWO (Flanders), which united 15 research groups in Flanders and abroad and organised a successful series of OPTIMESS workshops.

On the European level, the Composite Materials Group participated in the Composites-in-Transport network, followed by MOMENTUM Marie Curie Training Network. These two networks, active in succession for almost 10 years, set up an effective and sustainable research platform for the study and development of innovative composite materials applications for the rail, aerospace, maritime and automotive transport modes.

The Composite Materials Group plays an active role in CELC, the European Confederation on Flax and Hemp fibres. With Joris Baets as the technical advisor and Ignaas Verpoest as Chairman of the European Scientific Committee of CELC, KU Leuven is at the heart of the exciting industrial developments in this "traditional" agro-industry. It was, and is, a challenging, but rewarding, task to re-focus the whole value chain, from flax farmers through scutchers, hacklers and spinners, to weavers, towards the specific needs of the composites industry. The book "Flax fibres, a natural solution for the composites industry" (jointly published by CELC and JEC) and the impressive presentation of new flax preforms during the last JEC show (march 2013) indicate that this traditional industry is capable of revolutionising its processes and products in order to serve the composites industry.

6 VOLUME BOOK: COMPREHENSIVE COMPOSITE MATERIALS

In 2000, Ignaas Verpoest was invited to become a member of the Advisory Board on the six volume series of books "Comprehensive Composite Materials," edited by Antony Kelly and Carl Zweben. This impressive set of books present a complete overview of the state of the art of composites science and technology, and even 13 years later is still the best reference for all scientists entering the field of composites.

TEACHING ABROAD

Over the past thirty years, Ignaas Verpoest has taught on four continents. He taught workshops and intensive courses on several aspects of composites during his sabbatical leaves in Stanford University (USA), EPFL (Switzerland) and Kansai University (Japan) and during extended stays at the Institut Teknologi Bandung (Indonesia), Bangla Desh University of Engineering and Technology, RMIT (Australia), Cantho University and Hanoi University of Technology (Vietnam). In the framework of both Composites-on-Tour initiatives, he has also taught mixed audiences of designers and engineers in countries like Hungary, Slovenia, Italy, Spain, France, the Netherlands and the UK.

Stepan Lomov has delivered modular (20 teaching hours during one week) courses on Textile Composites, Textile Reinforcements for Composites, and Mechanics of Heterogeneous Media almost every academic year since 2001 in different locations: Goteborg, Liberec, St-Petersburg, Milan (three times), Singapore, and Osaka. The exam is taken by e-mail interaction with students afterwards. Some of the courses were organized within the framework of the Erasmus program of the European Union, others by the corresponding universities. These courses are almost fully based on the research in the Composite Materials Group. They "mirror" the corresponding courses in Leuven, of about the same size, but which are given over one semester.

Some members of the European Scientific Committee of CELC: Ignaas Verpoest, Joris Van Acker, Joris Baets, Hans Lilholt and Christoph Baley

Hermawan Judawisastra and Ignaas Verpoest at Institut Teknologi Bandung, Indonesia, 2009

Stepan Lomov teaching in St-Petersburg

HOME BUILT AND UNIQUE **EQUIPMENT**

FOR COMPOSITES MANUFACTURING & TESTING

In 1981, at the very beginning of composites research at KU Leuven, a "composites lab" literally had to be built from scratch in the Department of Metallurgy and Materials Engineering. Fortunately, the department has the unique policy that all equipment can be freely used by all research groups and that, in return, they all contribute to purchasing characterization and testing equipment for common use. Because of this policy, the basic mechanical testing and materials characterization apparatus was already available. Moreover, at the start of the Composite Materials Group, some funding was made available for the technical staff to start designing and building specific composites processing equipment. This approach of 'home built equipment' has been continued throughout the history of the Composite Materials Group. Gradually however, participation in larger research projects has allowed for the purchasing of specific equipment.

The role of the technical staff in the department cannot be underestimated. For 25 years, Jo Mariën led a small group of dedicated technicians, working mainly on the maintenance of existing machines and the development of new composites related equipment. The list of their names is long, but they all should be honored for their invaluable contribution to the growth of composites research at KU Leuven *(in reverse chronological order)*: Bart Pelgrims (coordinating the technical work since Jo Mariën's retirement in 2008), Kris Van de Staey, Marc Peeters, Manuël Adams, Pieter Alles, Iris Cuppens, Tom Vanderborght, Dirk Vranckx, Tim Niss, Tom Govaerts, Georges Swinnen, Marc Verbeeck, Guido Vandenplas, Geert Herbots, Katrien Verbrugge, Johan Vanhulst, Michaël Joris, An Cosaert, Philip Oris, Jan Hendrickx II, Jo Dendauw, Mario Deschutter, Luc Peeters, Joost De Vos, Louis Depré, Jan Hendrickx I and Theo Vermaelen.

In addition to the technicians mentioned above, many members from different sections of the technical staff of MTM have been extremely helpful in the development of the machines and software that facilitate our work, unfortunately they are too numerous to mention in full.

Similarly, it would be impossible to exhaustively present all of the equipment which is available nowadays in the Composite Materials Group at KU Leuven (the full list can be found on the website). In this chapter, we will highlight only the home-built equipment, and some rather unique processing, testing and characterization facilities that have been developed over the years. All of these will be presented briefly, but a full description is available on the group-website.

Weekly team meeting in 1996 (from left to right: Jo Mariën, Louis Depré, Geert Herbots, Guido Vandenplas, Mario Deschutter, Kris Van de Staey)

COMPOSITES PROCESSING EQUIPMENT

LAB-SCALE AND PILOT-SCALE PREPREGGERS

In the mid-90s, when Shell Laboratories in Louvain-la-Neuve decided to reduce their down-stream research on the use of their famous Epikote epoxy resins in composites, Jean Rivière approached us with an offer we could not reject: we would acquire their prepregging equipment, on the condition that we would keep it in perfect condition, and make it available for free whenever Shell would need it. Our technicians invested some time in making the equipment fully operational again, but it was worth the effort. The Composite Materials Group now has both a lab-scale and a pilot-scale prepregger, which is quite unique in Europe.

Drumwinder

Pilot scale prepregger

The **lab-scale prepregger** or 'drumwinder' allows us to make prepregs from just one spool of fibres, and is hence an extremely flexible and useful tool. All kinds of fibres (carbon, glass, flax, jute, silk, etc...) have been combined with a large variety of thermoset and thermoplastic matrices. In this process, the fibre bundle is taken off at the spool stand and is pulled through a drying/cleaning furnace. Subsequently, it is lead through a sizing bath before it is impregnated in a resin bath. In the next step, the fibre bundle is pulled through a die and over flattening pins to spread the fibres. Finally, the impregnated bundle passes over the guide roller and is wound around the drum, which rotates while translating laterally, producing a UD-prepreg.

The **pilot-scale prepregger** impregnates UD-fibre layers or textiles (to a width of 300 mm) with hot-melt resins. A thin resin layer is applied, together with the textile or fibres, between two transfer papers and it passes between the first nip rollers. Together, the three layer assembly passes the impregnation table, where the resin becomes less viscous and the impregnation is completed. The system then passes the B-stage plate where the polymerization of the resin (B-stage) occurs. Afterwards, the system is cooled down to room temperature and passes the chill plate. Finally, the top paper is removed and the prepreg is wound up.

CONVERTING SCRAP TO AUTOCLAVES

Every composites lab needs an **autoclave**, but at the start in the 90s the budget was not available to buy one. Thanks to the creativity and technical ingenuity of our technical staff, the problem was solved sooner than expected.

First, a small autoclave was built: two flat, heated steel plates were clamped in a 70 year-old Amsler compression testing machine for applying pressure. Between the plates, a normal composite lay-up for autoclaving could be built up, and heat, vacuum (through small holes in the bottom plate and a vacuum bag at the top), and pressure were applied using computer controlled cure cycles.

First autoclave

This temporary solution was soon made obsolete. In the framework of some consulting work on the fatigue of steel components in an electrical power plant in Mol (Belgium), Jo Mariën collaborated with Julien De Schrijver of EBES, developing a specific set-up for applying combined tension-torsion fatigue loads on tubular specimens. During their many discussions, Jo mentioned the need for a 'real' autoclave, and Julien came up with the idea to convert a heat exchanger (in fact a pressure vessel operated at high temperature), that was ready to be scrapped at the power plant. Since heat and pressure are common features of a heat exchanger and an autoclave, they started preparing the conversion of the pressure vessel, by adding a heating and a ventilation system, process control equipment, specimen lay-up table, etc.... After successful proof testing, the autoclave started its 25 year career as one the work horses of the composites lab.

A similar coincidence was at the origin of the second autoclave. After a jazz concert, Ignaas Verpoest met Josée Houben, director of KU Leuven's Research Coordination Office, and her husband, who happened to manage the truck tire re-treading company, Bandag. It turned out that this company would scrap a number of autoclaves with the shape of a single truck tire. Again, high pressure and temperature made them an ideal candidate to be converted into a composite autoclave. Jo Mariën and his team converted an initial one, but their designs were used by others to do the same. The blue Bandag autoclaves are still in service at the Institut Teknologi Bandung (Indonesia) and Cantho University (Vietnam).

The heat exchanger of EBES converted into an autoclave (above) and Bandag autoclave installed in Indonesia (below)

BUILDING OUR OWN RTMS

Resin Transfer Moulding is the second most important composites processing technology, gaining more importance starting in the early 90s. Jo Mariën and his team decided again to build their own **RTM**, inspired by the best partial solutions of various commercial machines, and combining it with their excellent technical knowhow in mechanical construction, electrical heating, vacuum and pressure systems and electronic control units.

In the RTM process, first a dry textile perform (the reinforcement) is placed into a mould cavity. Then the mould is closed and a thermoset resin is injected from a resin pot into the mould with low pressure, sometimes adding vacuum at the exit side of the mould. After the reinforcement is fully impregnated, the injection port is closed and the resin is allowed to cure. When the resin is cured the part can be demolded.
The flat mould halves of the first RTM, built by the technicians of MTM in the mid-90s was opened and closed manually with bolts. In the mid-2000s, a second RTM was built with a hydraulic actuator providing the counterforce against overpressure in the mould, this reduced the process cycle duration. In another process, the so-called 'light-RTM,' the same system of resin pot and vacuum can also be used. In the light RTM, the upper mould half is replaced by a more flexible glass fibre composite mould, allowing only small overpressures, but reducing the cost, certainly when parts with complex shapes have to be manufactured.

A further simplification is the Vacuum Assisted Resin **Infusion** (VARI): only one mould half is solid, the other side is just a vacuum foil, and the resin is infused by the pressure difference between the ambient in the resin pot and the vacuum at the exit side of the mould. Different heated plates are now available to be used as the bottom mould, and combined with the vacuum pumps. VARI has become the second working horse in composites processing at MTM.

First RTM (above) **and second RTM** (below)

Light-RTM (top) and **Vacuum Assisted Resin Infusion - VARI** (bottom)

(top) **Old Fontijne press with own build preheating and** (bottom) **new Fontijne press station**

COMPRESSION MOULDING: FROM SMALL AND SIMPLE TO BIG AND ALMOST INDUSTRIAL

In the same trend as with the autoclave and RTM processes, compression moulding of thermoplastic composites at KU Leuven also started with a moderate home-built, heated press. It was essentially the same set-up as developed for the first, flat autoclave, only a non-perforated bottom plate was used. The small size of the moulds was a major disadvantage, except for in the initial research on the effect of crystallinity in thermoplastic composites: for this, a special, high speed cooling system was built, allowing cooling rates up to 2000°C/min.

To overcome the small size of the first home built press, a second-hand professional press was acquired from the Shell labs in Louvain-la-Neuve, together with the transfer of the drumwinder and prepregger. Several adaptations to this **Fontijne-press** had to be carried out, and Bart Pelgrims designed and built an automatic pre-heating and feeding system. A major advantage of this system was that not only flat plates could be manufactured. Complex moulds of limited size (600x600 mm) could be built into the press.

The increase in research projects involving thermoplastic matrices required a further expansion of the compression moulding equipment. A specialized hot press was aquired, manufactured by the French company **Pinette** Emidecau Industries (PEI). It has a hot and a cold zone, allowing for fast cooling rates of at least 100°C/min. Recently, a home-built computer control system has been installed, with numerous preprogrammed heating and cooling cycles.

A major expansion was realized in collaboration with the Department of Mechanical Engineering (prof. Dirk Vandepitte), after winning a highly competitive grant from the Flemish government (mid 90's). A pilot-scale compression moulding press was built by a consortium of Flemish companies, led by HACO, and allowed us to realize 1m² large parts with a process close to industrial reality, including infrared preheating. This **HACO-press** played a crucial role in the development of Samsonite's composite suitcases. Technicians of KU Leuven intensively collaborated with technicians of Samsonite to adapt the press so that it could handle the CURV®-sheets (see Chapter 3). Recently, the press has been extended with large flat moulds, and an adapted hydraulic system, so that special layups of thermoplastic sheets can be produced, in the framework of the HIVOCOMP-project and projects of SLC.

For scientific experiments which require a more precise temperature control, and faster heating and cooling rates, a second **Fontijne** press has been acquired in 2012.

The Pinette press with hot and cold zone (left) **and** (right) **the large pilot-scale compression molding press HACO**

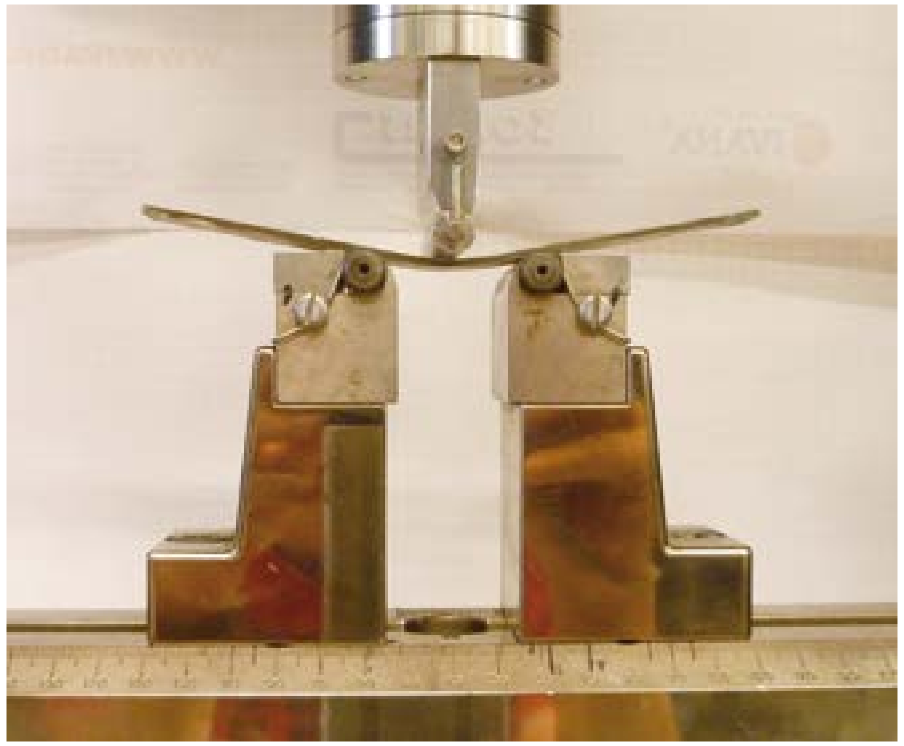
COMPOSITES TESTING EQUIPMENT

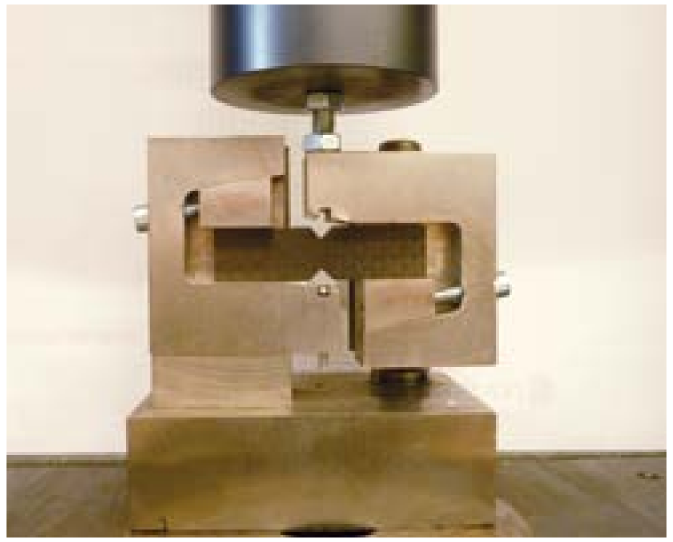
As mentioned in the introduction, the Composite Materials Group has access to all the testing and characterization equipment of the Department of Metallurgy and Materials Engineering. Moreover, in the framework of LeuvenMRC, important polymer characterization equipment is also available in the Departments of Chemistry and Chemical Engineering.
Hence, in the following only specific, composites oriented adaptations of existing testing equipment, or home-built apparatus will be presented. As there are so many, they will only be described briefly, and more information can be found on the group-website.

MECHANICAL TESTING OF COMPOSITES

Five **mechanical testing machines** with different loading capacity (from 5 N to 250 kN) are available at MTM (see website). They are heavily used for testing of fibres, textiles and composites, and many special grips, fixtures and adaptations have been designed and home-built over the past three decades. Moreover, sometimes completely new mechanical testing machines had to be developed.

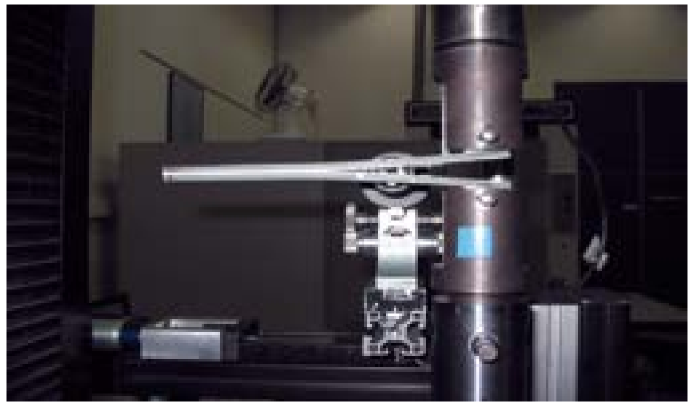
For measuring specific mechanical properties of composites, several grips and fixtures have been designed and manufactured in-house. For characterizing the deformability of **textiles, preforms and**

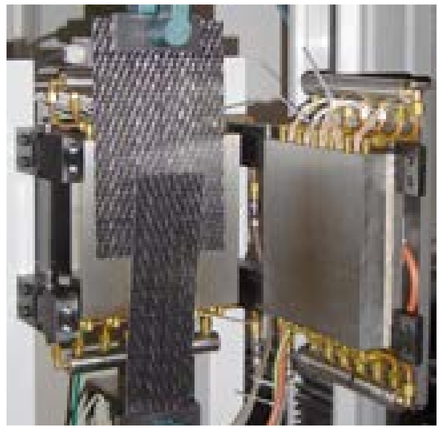


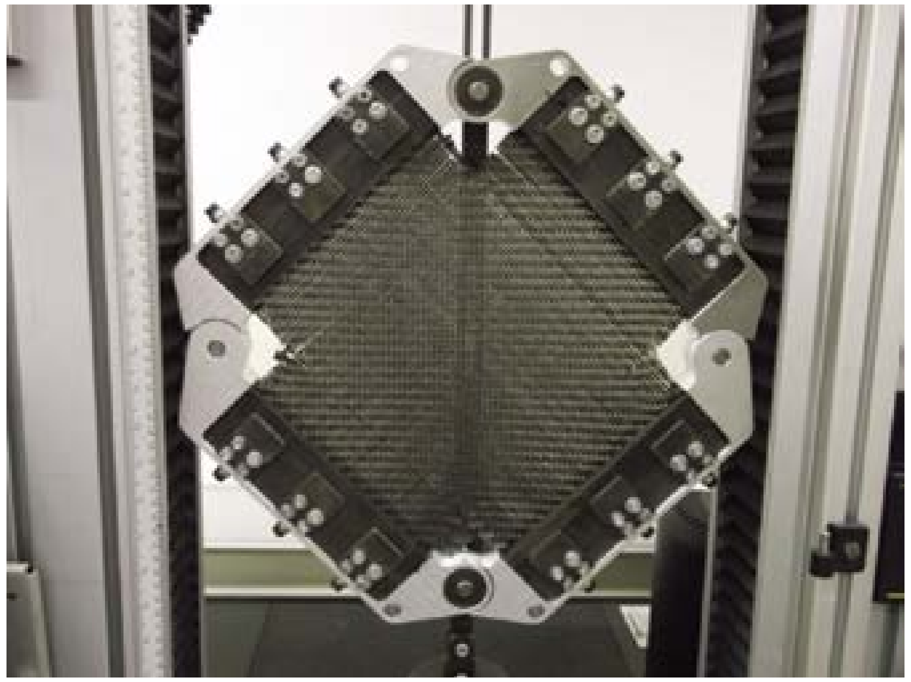


(top left) **Tensile testing machine,** (top right) **Bending test**
(Below) **Iosipescu setup for in plane shear measurements**

Interlaminar fracture toughness testing by aDCB (double cantilever beam) test

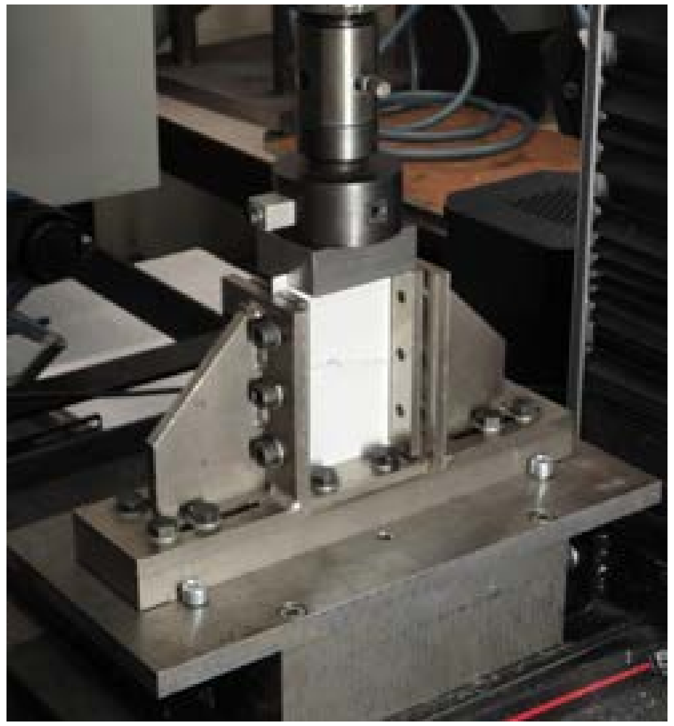




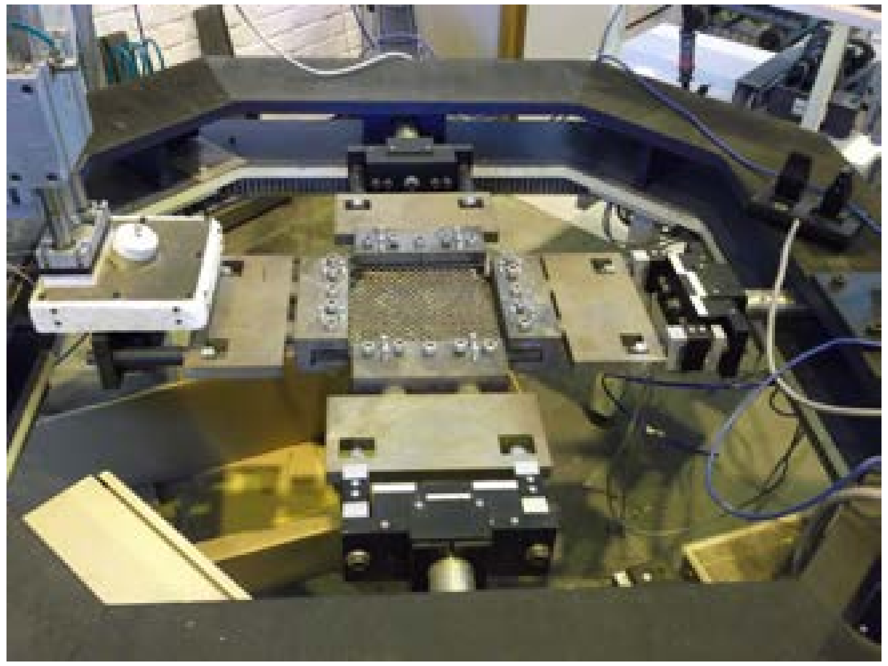


(above) **Device for measuring interply friction at high temperature, a useful device for simulations of thermoplastic composites**
(right) **Picture frame test setup for characterization of the draping behaviour**

(below left) **Open hole compression setup**
and (below right) **Compression after impact**



(left, from top to bottom)
Fragmentation tester under microscope, Biaxial tester used for the shear compression behaviour of foams and Biaxial tester



(below) **Small tensile machine for single fibre testing** and **Tensiometer**

prepregs, special fixtures had to be developed.
Single fibres require very specific testing equipment:

- For single fibre testing, a table top Instron with low load capacity, and hence high precision, was acquired. It is equipped with special grips for testing single fibres
- The interface strength can also be measured using the **fragmentation test.** A special tensile test fixture was acquired from the Department of Chemistry, and can be mounted under the microscope to follow the fibre fragmentation and debonding.
- High-precision **tensiometer** for the determination of the surface tension, interfacial tension of liquids, and surface energy of solids.

Sometimes, a completely new testing machine needed to be developed. For assessing the drapability of textiles, apart from the shear characteristics (tested using the 'picture frame tester', see above), the biaxial extensibility of a textile is important. In the mid-90's, Jo Mariën and his team designed and built a unique **biaxial tester** with four independently computer controlled axes; output consists of the force-displacement curves in the two principal directions. Heating plates can be moved above and below the test specimen, to simulate the real conditions during compression moulding of thermoplastic composite sheets.

The equipment has since then been used for other purposes, like combined compression and shear testing of foams, etc...

FATIGUE TESTING OF COMPOSITES

Fatigue behaviour is of extreme importance for the lifetime of materials. Fatigue testing at MTM can be performed on four different servo-hydraulic and one electro-mechanic machine with different loading capacities, in tension (between 7 and 160 kN), compression, bending, torsion, internal pressure (for tubes) or a combination of these loading modes.

Usually, similar fixtures and grips as those used for metals and ceramics are used for composite testing. But some distinctive fixtures for special tests have been acquired or built like a reverse four point bending setup, initially designed for the testing of tennis racket frames.

Two of the five available fatigue testing machines

IMPACT TESTING OF COMPOSITES

Whereas the impact properties of metals and polymers are tested by using pendulum testers according to Izod or Charpy standards, composite laminates are tested by impacting them perpendicularly to the laminate surface with an impactor having a certain amount of kinetic energy. During the test, the amount of absorbed energy and, if possible, the loads and displacements of the impactor are measured. After the test the damage is evaluated using various NDT-techniques.
As this type of testing is fundamentally different from the usual pendulum tests, an **Instrumented Falling Weight Impact Tester** (IFWIT) had to be built. It is fully instrumented, allowing the measurement of loads and impactor head displacements, and hence the calculation of absorbed energies can be done in multiple ways. The IFWIT is equipped with different impactors and plate gripping systems. Recently, it has been extended with a rotating belt replacing the laminate gripping system, on which a dummy head can be droped. In this way, not only the energy absorption capacity of bicycle helmets can be assessed, but also the effect of different foam types on the rotational acceleration of the head.
A second impact tester was donated by Huntsman, and has the additional capacity of carrying out impact tests at low temperatures.

Home build impacter

Home made helmet tester with dummy head and rotating belt as bottom plate to realistically mimick oblique impacts

SPECIFIC EQUIPMENT FOR NON-DESTRUCTIVE TESTING OF COMPOSITES

The Composite Materials Group is strongly linked to the Non-Destructive Testing group of prof. Martine Wevers. In the early 80s, the NDT-research got a boost due to the specific requirements of damage detection in composites. Acoustic emission techniques were introduced during Martine Wevers' PhD thesis.

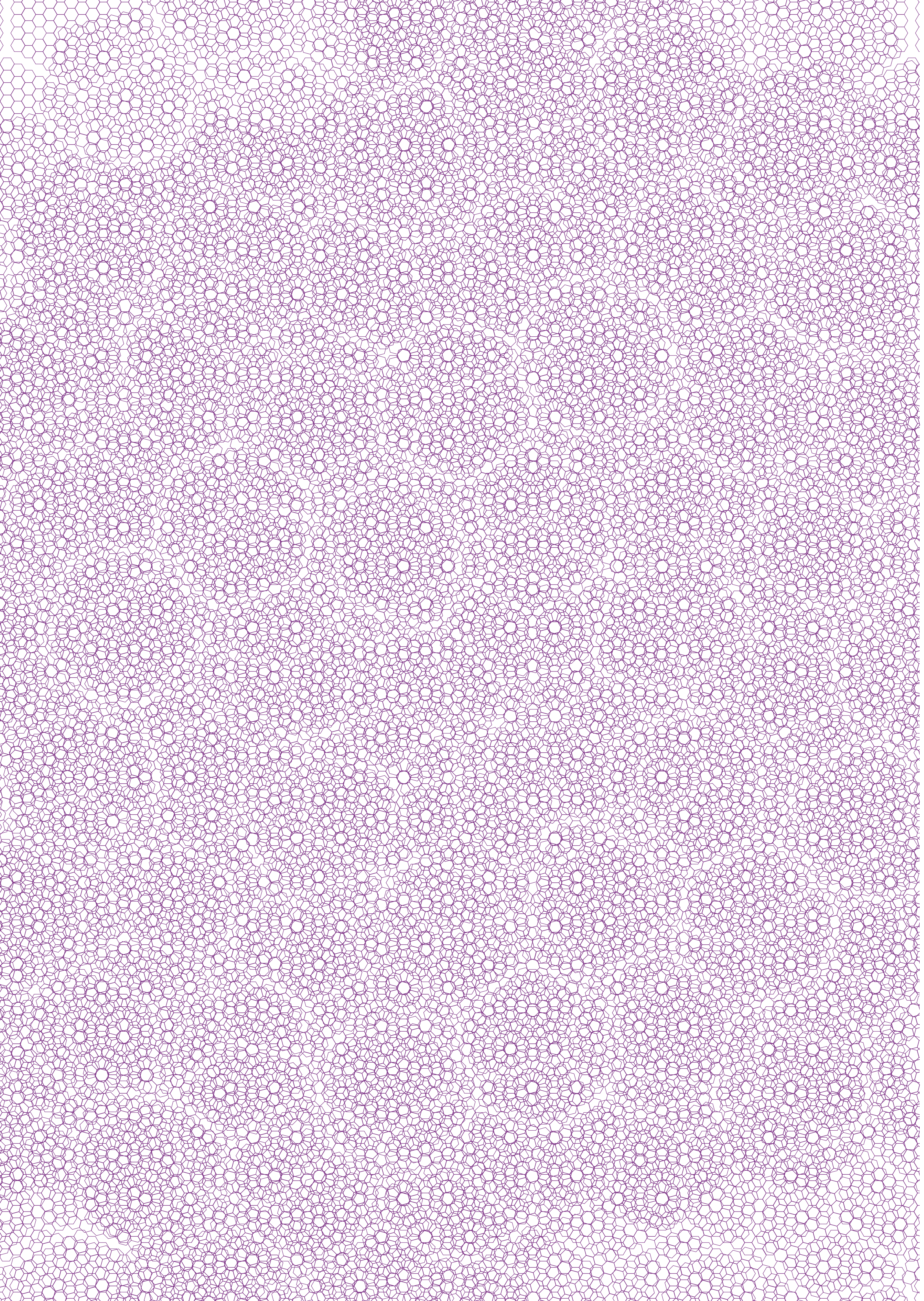
Later on many other NDT-techniques were added: **ultrasonic C-scan, fibre optics, X-ray computed tomography and acoustic emission** (more information can be found on the website of MTM's research group on non-destructive testing).

Recently, **strain mapping techniques** are heavily used for various purposes: simply as a non-contacting extensometer, but more frequently to quantify the inhomogeneous strain fields in textile composites or around defects or holes. Two Limess strain mapping systems are available now, enabling us to measure full-field surface strain fields by comparing the images of the same region before, during and after deformation.

X-ray tomography machine

Ultrasonic C-scan

Strain mapping equipment in use during a tensile test



PHD THESES
in the Composite Materials Group at KU Leuven

Martine Wevers
Identification of fatigue failure modes in carbon fibre reinforced composites
7/05/1987
Professor, Head of the Department MTM, KU Leuven, Belgium

Ronald Van Daele
Damage development in carbon fibre composites during monotonic loading *(in Dutch)*
13/06/1990
R&D engineer at STYRON, Terneuzen, The Netherlands

Bernard Goffaux
The relation between fracture toughness and microstructure in thermoplastic polymers and composites
2/06/1993
Global market manager, Solvay, Belgium

Muriel Desaeger
An integrated theoretical and experimental study of the fibre-matrix interface in carbon-epoxy composites
23/09/1993
Senior Principal Technologist, Toyota Motor Europe, Belgium

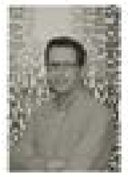
Jan Ivens
Mechanical properties and damage development in carbon fibre reinforced plastics: the effects of the fibre matrix interface
30/09/1993
Associate professor, Head of Department of Engineering Technology, Thomas More Mechelen University College, KU Leuven, Belgium

Luc Lammerant
The interaction of matrix cracks and delaminations during impact of composites *(in Dutch)*
1/03/1995
Senior Project Manager R&D, Heraeus Electro Nite, Belgium

Vassilios Efstratiou
Investigation of the effect of the 2.5-D carbon fabric construction on fabric reinforced/polymer matrix composite toughness
25/04/1995
Head of Section, Public Power Corporation, Greece

Aart-Willem Van Vuure
Composite panels based on woven sandwich-fabric preforms
9/04/1997
Assistant Professor, GroupT University College, KU Leuven, Belgium

Bart Gommers
The elastic properties of knitted fabric composites
25/11/1997
Process R&D and product quality, ArcelorMittal, Belgium



Philippe Vandeurzen
Structure-performance modelling of two-dimensional woven fabric composites
23/03/1998
CFO, De Eik NV, Belgium

Sofie Baeten
Impregnation and consolidation of low cost textile reinforced thermoplastic composites
28/09/1999
Partner, Capital-E, Belgium

Dirk Philips
Characterization and development of 3D-knitted composites
21/09/1999
Consultant for Altran at Electrabel, Belgium

Wei Wu
Stress transfer through the fibre-matrix interphse in axially loaded composites
1/03/1999
Teaching professor, Temple University, USA

Gert Huysmans
Unified micromechanical models for textile composites
9/02/2000
Technology specialist, ETAP Lighting NV, Belgium

Edgard Jacobs
Stiffness and strength of unidirectional composites reinforced with coated fibres (in Dutch)
13/10/2000

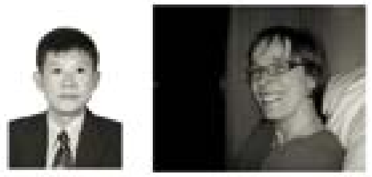
Yiwen Luo
Resin transfer moulding of knitted fabric reinforced composites
29/05/2001
Global Innovation Director – Rubber Reinforcement, Bekaert, China

Hermawan Judawisastra
Damage tolerance of composite sandwich panels containing 3D-woven sandwich fabrics
8/10/2002
Lecturer at Institut Teknologi Bandung, Indonesia

Surya Darma Pandita
Damage tolerance of knitted and woven fabric composites
17/12/2002
Research Fellow, University of Birmingham, UK

Andreas Prodromou
Mesomechanical modelling of textile composites utilising a cell method
27/05/2004
Lecturer at Cyprus University of Technology

Paul M. Wambua
Protective low price composite materials based on natural fibres
30/06/2004
Professor and Deputy Principal (Academic Affairs), Kirinyaga University College, Kenya

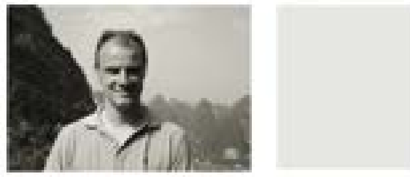


Thanh Chi Truong
The mechanical performance and damage of multi-axial multi-ply carbon fabric reinforced composites
18/11/2005
Lecturer, Chemical Engineering Department, Cantho University, Vietnam

Isabel Van de Weyenberg
Flax fibres as a reinforcement for epoxy composites
8/12/2005
Research engineer, Flanders' DRIVE, Belgium

Hilde Parton
Characterisation of the in-situ polymerisation production process for continuous fibre reinforced thermoplastics
14/02/2006
Group Manager - Wiper system base development, Bosch, Belgium

Xinyu (Darren) Fan
Investigation on processing and mechanical properties of the continuously produced thermoplastic honeycomb
6/04/2006
Professor, Ningbo Institute of Material Technology and Engineering, China



Frederik Desplentere
Multiscale modelling of stochastic effects in mould filling simulations for thermoplastic composites
29/01/2007
Assistant Professor, Head of "Polymer processing and Light Weight structures" group, KULAB University College, KU Leuven , Belgium

Philipp Johann Bratfisch
Development of production equipment for thermoplastic folded honeycomb sandwich cores
21/02/2007
Manager Regulations and Technical Affairs, Nissan Technical Centre Europe, Belgium

Joris Baets
Toughening of in-situ polymerized cyclic butyleneterephthalate for use in continuous fibre reinforced thermoplastic composites
22/12/2008
Postdoctoral researcher, KU Leuven, Belgium

Bart Verleye
Computation of the permeability of multi-scale porous media with application to technical textiles
20/03/2008
High Performance Computing Applications Support Specialist, University of Auckland, New Zealand

An Willems
Forming simulation of textile reinforced composite shell structures
2/12/2008
Composite Calculation Engineer, Techspace Aero (SAFRAN GROUP), Belgium

Dmitry Ivanov
Damage analysis of textile composites
13/05/2009
Lecturer, Composites Manufacturing, University of Bristol, UK

Maarten Moesen
Modeling of the geometry and mechanical behavior of bone scaffolds
16/06/2009
Polymer Physicist Computational Modeling, HUNTSMAN, Belgium

Katleen Vallons
The behaviour of carbon fibre-epoxy NCF composites under various mechanical loading conditions
13/07/2009
Postdoctoral researcher, KU Leuven, Belgium

Kristof Vanclooster
Forming of multilayered fabric reinforced thermoplastic composites
30/06/2010
Researcher, Toray Industries, Inc, Japan

Ichiro Taketa
Analysis of failure mechanics and hybrid effects in carbon fibre reinforced thermoplastic composites
5/04/2011
Senior Researcher, Toray Industries, Inc., Japan

Jian Xu
Meso-scale finite element fatigue modelling of textile composite materials
12/09/2011
Researcher and Developer in Automated Fibre/Tape Placement, Compositence GmbH, Germany

Ngoc Tran Le Quan
Polymer Composite Materials based on Coconut Fibres
10/01/2013
Postdoctoral researcher, KU Leuven, Belgium

CURRENT PHD RESEARCHERS
in the Composite Materials Group at KU Leuven

(date corresponds to start of PhD)

Guillaume Perie
Modelling of internal structure and mechancial properties of angle interlock three-dimentional composites
October 2006

Mohammadali Aravand
New concepts for nano-engineered polymer composites
August 2010

Valentin Romanov
Development of modeling tools for mechanical behavior of fibre-reinforced composites modified with carbon nanotubes
September 2011

Jochan Pflug
Continuously Produced Honeycomb Core Materials
1997

Andy Vanaerschot
Characterisation of the spatial variability in the mechanical properties of textile composites by multi-scale modelling and experimental validation
August 2010

Dieter Perremans
Improvement of the interphase strength and moisture sensitivity of flax fibre biocomposites October 2011

Kelly Vanden Bosche
Development and Characterization of Novel Anisotropic Foam for Bicycle Helmets
January 2008

Yentl Swolfs
Hybridization of self-reinforced composites: verifying and modelling a new hybrid concept
August 2010

Farida Bensadoun
Optimization of flax fibre reinforced composites for high performance cost-effective Applications
February 2012

Nhan Vo Hong
Manufacturing gluten resin based natural fibre composites
March 2009

Michaël Callens
Development of nano-engineered steel fibre composites
October 2010

Yasmine Abdin
Micro-Mechanical and Fatigue Modeling of Short Steel Fibre Reinforced Composites
April 2012

Eduardo Trujillo
Polymer composite materials based on bamboo fibres
October 2009

Bart Buffel
Fibre reinforced polyurethane sandwich structures: characterisation, optimization and modelling"
October 2010

Seyed Ahmad Tabatabaei
Meso-FE and damage modelling of self reinforced composites
June 2012

Carlos Fuentes Rojas
Interfacial adhesion on mechanical behaviour of natural and synthetic fibre composites
October 2009

Niels De Greef
Carbon nanotubes in nano-engineered polymer composites
October 2010

Ilya Straumit
Estimation of composite's mechanical properties on the basis of X-ray computed tomography data
January 2013

Lina Osorio
Microstructural analysis and mechanical behaviour of bamboo fibres and bamboo fibre composites
October 2009

Atul Jain
Fatigue life prediction of random fibre composites using hybrid multiscale modeling methods
July 2011

Yasmine Mosleh
Development and evaluation of anisotropic foams for improved rotational impact resistance of bicycle helmets
February 2013

Oksana Shishkina
Multi-level compressive behaviour of cellular nanocompoites: characterisation and modelling
March 2010

Bart Van Mieghem
An intelligent experimental approach for the optimization of the process parameters for the thermoforming of plastics and composites
September 2011

PATENTS

IN THE COMPOSITE MATERIALS GROUP OF KU LEUVEN

The very first invention in the Composite Materials Group was never patented. In 1985, Ignaas Verpoest proposed to the Schlegel company (Gistel, Belgium) to use their distance weaves for making integrally woven sandwich panels by impregnating them with a thermoset resin (see full story in Chapter 1). Later, when he discovered that the same idea had been patented by the German company Vorwerk, some weeks after the initial labscale tests in KU Leuven, Ignaas realized the importance of patents.

Since then, the protection of "intellectual property" has been a continuous point of focus. With each new development, the question is asked whether the idea is worth patenting. Answering this question is not easy. There are first the technicalities of patents: which innovations are patentable? How to write a good patent? Which procedures for filing to follow? And then there are the consequences of filing a patent: what are the costs? How to exploit a patent? Do patents not hinder scientific publications? And so on...

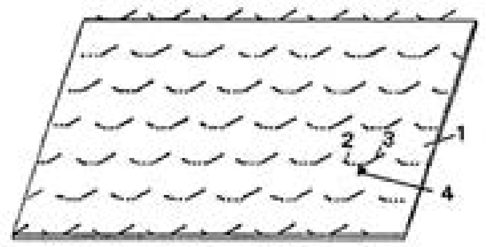
Over the past thirty years, the Composite Materials Group has gone through a steep learning curve on this subject. Thanks to the excellent guidance of KU Leuven's tech-transfer organization, Leuven Research and Development (LRD), experience was built up in all aspects of patenting, and an important portfolio of 15 patents has been realized (two of which are filed but not yet published, and hence will not be described in this chapter). In the following text, these patents will be presented in six thematic groups, proving the diversity of the research and innovations in the Composite Materials Group of KU Leuven. For each patent, the contents will be briefly described (and an original drawing the patent application will be shown, where appropriate), and the status of exploitation will be discussed.

3D- OR DISTANCE WEAVES FOR COMPOSITE SANDWICH PANELS

After the disappointment of not having patented the initial idea of 3D- or distance weaves for composite sandwich panels, a collaboration was started with the Dutch company Parabeam, owning weaving looms for this special type of weaves. Parabeam made a deal with Vorwerk, backed up by KU Leuven's earlier lab-scale developments (which were fortunately well documented in our lab books), and started the production of glass fibre 3D-weaves. Twenty five years later, Parabeam is still the world's leading manufacturer of these materials.

The original process of the Schlegel company, namely cutting the pile threads to create two 2D-weaves with short cut yarns sticking out of the surface (a technology also used to weave carpets!), inspired Ignaas Verpoest to another innovation: these short fibres standing out of the textile surface could increase the resistance to the growth of delaminations when such weaves would be used as normal 2D-reinforcements for composites. They would indeed reinforce the resin rich interlaminar layer, one of the weak points in composite laminates. Interlaminar fracture toughness tests proved that the idea was valid, and it was protected, together with Parabeam, in two patents, but did not result in a commercial activity by them. Afterwards, in our scientific publications we used the name "2.5D weaves", indicating that the yarns in third dimension have been cut.

EP0463482
Length of cloth for compound structures
Inventors: Ignace Verpoest; Peter Van der Vleuten (parabeam).
Priority date: 13/06/1991



US5271982
Textile material for composite construction
Inventors: Ignace Verpoest; Peter Van der Vleuten (parabeam)
Priority date: 19/02/1991

3D- OR DISTANCE KNITS FOR MULTIFUNCTIONAL COMPOSITE SANDWICH MATERIALS

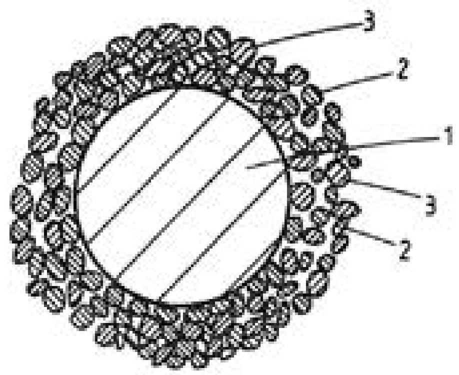
3D-weaves have become a commercial success for flat panels or single curved shapes (like underground containers), but double curved surfaces are impossible. As we got more involved in the textile industry, we discovered that distance knits also existed, and that they have two additional advantages. First, due to the knitted loop structure, the knitted skins are extensible and hence they can be easily draped over double curved surfaces. Second, knitting allows the creation of a large variety of patterns, creating not only fully closed but also open skins. The knitting loop structure, however, prevents the piles from standing up by themselves (like in 3D-weaves), and hence monofilament yarns had to be used as pile yarns. This created a new problem, namely that during impregnation with a thermoset to create a composite sandwich, these monofilaments could not be impregnated.

The idea of creating double curved, open, and hence ventilating knitted sandwich materials was protected in an initial patent, originally submitted with partners of a local composites company (IPA), who later transferred the patent fully to KU Leuven. The problem of the impossible impregnation of the monofilament pile yarns was solved by the use of DREF-spun yarns, with a monofilament core and a multifilament outer sheath. This idea was protected in a second patent.

Several attempts were made to find applications for these patents (see Chapter 2 of the book). In the medical area it was proposed and evaluated as an alternative, breathable material for casts and splints, in collaboration with companies like Smith&Nephew and Johnson&Johnson. We even went as far as to clinical trials, but a real commercial product could not be developed. Later on, it was found out that other companies commercialized slightly different products, not covered by our patent, but certainly inspired by it.

WO9401272
Composite material and a composite structure based on a three-dimensional textile structure
Inventors: Ignaas Verpoest, Joris Van Raemdonck, Willem Amesz and Willy De Meyer (IPA)
Priority date: 13/07/1992

WO9631336
Method for obtaining a three-dimensional textile product, thread used therein, composite materials obtained with this thread and according to this method
Inventors: Ignaas Verpoest, Joris Van Raemdonck and Willy De Meyer (IPA)
Priority date: 04/04/1995



ANISOTROPIC FOAMS FOR BICYCLE HELMETS

During the development of the 3D-knitted sandwich materials, a prototype bicycle helmet was produced, exploiting the double curving and breathability advantages, described in the 3D-knit patent. About ten years later, Ignaas Verpoest was invited by professors Jan Goffin (Neurosurgery), Georges Van der Perre and Jos Vander Sloten (Biomechanics) to participate in a project on bicycle helmets. One of their important findings was that during a bicycle accident, the head experiences complex impact loading which not only results in translational acceleration, but also rotational acceleration which can lead to serious brain damage. He then proposed to use a material that would be weaker in shear than in transverse compression, inspired by the 3D-knitted helmet that was made ten years earlier.

Because the properties of the 3D-knitted materials were not so easy to manipulate, an alternative was found in the application of anisotropic foams. By controlling the degree of anisotropy, the ratio of compression to shear resistance could be tuned, and hence the rotational acceleration reduced while keeping the normal impact energy absorbing function of a bicycle helmet. Using existing anisotropic foams, produced in flat sheets and manually cut and bent into a helmet, the concept of reducing the rotational acceleration was proven during dummy head impact tests. An initial patent on the use of anisotropic foams in helmets was filed in 2004 .

The next challenge was to invent an anisotropic foam material that could be formed in-situ, during the production of a bicycle helmet with a complex shape (with many ventilation holes). By coincidence, a collaboration had been started around the same period with the University of Valladolid, within the framework of a European project on foams for sandwich structures in windmill blades. The experience of prof. Miguel Angel Rodriguez–Perez allowed Kelly VandenBosche to develop a novel foaming process that resulted in a controllable degree of anisotropy during her PhD, co-guided by Jan Ivens. A second patent on this invention was jointly filed with the University of Valladolid in 2011. Discussions are on-going with bicycle helmet manufacturers to commercialize the invention (see also Chapter 4).

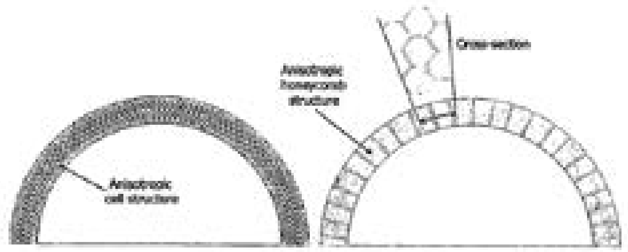
WO2006005143

Protective Helmet

Inventors: Bart Depreitere; Jan Goffin; Carl Van Lierde; Bart Haex; Jos Vander Sloten; Remy Van Audekercke; George Van Der Perre; Ignaas Verpoest; Peter Verschueren; Hans Delye

Priority date: 13/07/2004

A protective helmet is described comprising: an outer layer (1); an inner layer (5) for contact with a head of a wearer; and an intermediate layer (3, 4) comprising an anisotropic cellular material comprising cells having cell walls, the anisotropic cellular material having a relatively low resistance against deformation resulting from tangential forces on the helmet. The anisotropic material can be a foam or honeycomb material. The foam is preferably a closed cell foam. The helmet allows tangential impacts to the helmet which cause less rotational acceleration or deceleration of the head of the wearer compared to helmets using isotropic foams while still absorbing a significant amount of rotational energy.



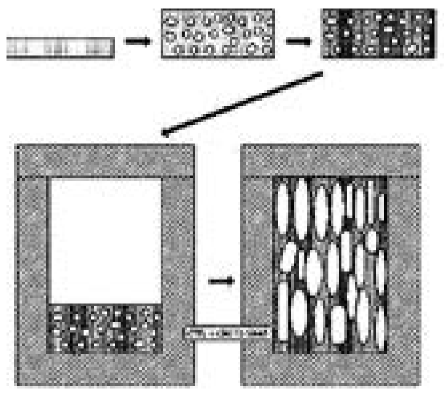
WO2013030318

Complexly Shaped Anisotropic Foam Manufacturing

Inventors: Kelly VandenBosche, Ignace Verpoest and Jan Ivens; Miguel Angel Rodriguez–Perez (Universidad de Valladolid)

Priority date: 31/08/2011

The present invention relates to a novel method of manufacturing of anisotropic cellular materials using a multi-step expansion process, matrix stabilization, and directed foam growth directions. This method is useful for customizing the cellular architecture of a foam such that specific desired macroscopic properties can be obtained, such as: density, the plateau strength in the growth direction, the ratio between the stiffness in orthotropic directions (anisotropy), the shear stiffness, ratio between thermal conductivities in different directions, etc...



CONTINUOUSLY PRODUCED FOLDED HONEYCOMBS

The complete story of the invention of a novel method to produce honeycomb cores has been extensively explained in Chapter 3. The initial ideas of Jochen Pflug, the support of Ignaas Verpoest, a string of IWT-projects, and the collaboration with prof. Vandepitte at Mechanical Engineering have together resulted in three strong patents. These patents formed the basis for the creation of the spin-off company, Econcore. Under its license, Thermhex-type honeycomb cores are now produced on eight production lines in six different countries on three continents.

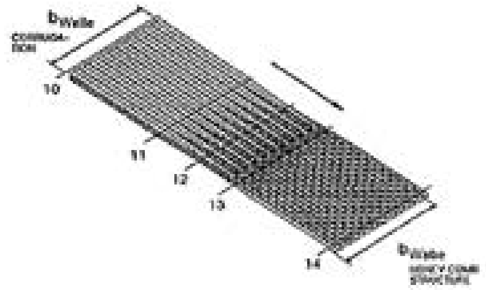
WO0058080

Folded Honeycomb Structure Consisting Of Corrugated Paperboard And Method And Device For Producing The Same

Inventors: Jochen Pflug; Ignaas Verpoest

Priority date: 26/03/1999

... According to the inventive method for producing the folded honeycomb structure, interconnected corrugated core strips are produced first by making a number of longitudinal scores in a corrugated core web. These corrugated core strips are then alternately rotated through 90 DEG respectively so that the cover layer strips fold and the folded honeycomb structure is formed. ...



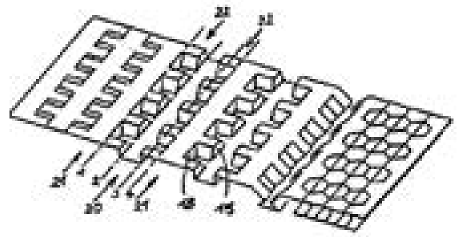
WO0032382

Thermoplastic Folded Honeycomb Structure And Method For The Production Thereof

Inventors: Jochen Pflug; Ignaas Verpoest.

Priority date: 20/10/1998

A thermoplastic folded honeycomb structure and method for the production thereof. A strip of material is plastically deformed perpendicular to the plane of said material and folded in the direction of conveyance until the cell walls meet and are joined.



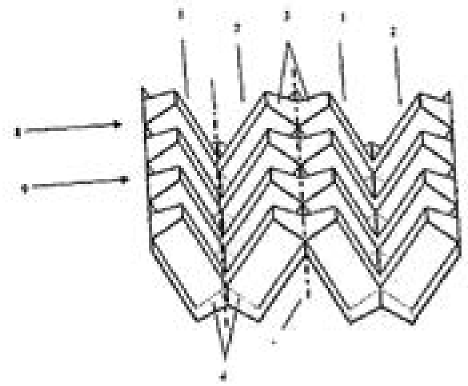
WO2006053407

Half Closed Thermoplastic Honeycomb, Their Production Process And Equipment To Produce

Inventors: Jochen Pflug; Ignaas Verpoest

Priority date: 19/11/2004

A half closed thermoplastic folded honeycomb structure is described which is produced from a continuous web of material by plastic deformation perpendicular to the plane of the material to thereby form half-hexagonal cell walls and small connecting areas. By folding in the direction of conveyance the cell walls meet to thereby form the honeycomb structure.



BIOBASED COMPOSITE MATERIALS

After having attended a 'workshop for designers' in the framework of the first Composites-on-Tour (see Chapter 3), Nedda El-Asmar, one of Belgium's top-designers, asked Ignaas Verpoest whether silk fibres could be used as reinforcement for composites. As a silversmith, she had been designing for Puiforcat, a division of the French luxury goods company Hermès, famous for their silk "carré's".

Nedda arranged a meeting with Corinne Poux, R&D manager at Hermès, who's enthusiastic reaction opened the doors to this house full of tradition. A project was started to explore silk fibre composites, with research engineer Jan Vanderbeke, co-guided by Aart van Vuure. In this project, different fibre-matrix combinations were explored. Extremely high impact resistance was obtained by combining the reasonably stiff but very tough silk fibres with high toughness thermoplastic matrices. Unfortunately, this exciting innovation did not cross the border to prototyping.

A similar coincidence was the foundation of a second patent on bio-based composites. Initial work on starch based polymers (see Chapter 3) had resulted in a collaboration with prof. Jan Delcour of the Faculty of Bio-Engineering. Being a specialist in gluten, the protein fraction of wheat (or corn,...) flour, he suggested exploring the possibilities of using gluten as a polymer, inspired by recent publications. Dara Woerdeman, a visiting postdoctoral researcher from NIST (USA) in 2001 with a strong chemistry background, was intrigued by the question of how to modify the chemistry of these proteins in order to make the resulting polymer less brittle. Thiol was found to solve the problem, and the use of thiol-based modifiers was patented. This patent then formed the basis for two large research projects, involving six PhD-students, and will soon result in new patented innovations which cannot yet be disclosed.

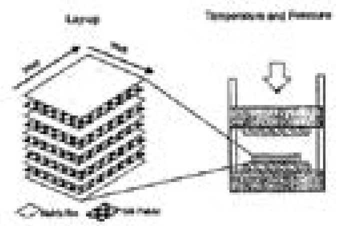
WO2007110758

Silk Fibre Composites

Inventors: Ignace Verpoest, Aart Willem Van Vuure, Nedda El Asmar and Jan Vanderbeke

Priority date: 24/03/2006

The present invention provides silk fibre reinforced composite materials comprising a thermoplastic polymer matrix, which are relatively light, whilst having a high impact resistance. The silk fibre reinforced composite materials of the present invention allow for an optimal dissipation of the impact energy such that they have a penetration resistance higher than 20 J per mm of plate thickness.... Due to the high impact resistance of the fibrous composite material ..., panels or shells comprising such composites are particularly useful for the manufacture of objects, which in the course of their life cycle are subject to shocks or at risk of penetration.



WO2004029135

Gluten Biopolymers

Inventors: Dara Woerdeman, Ignaas Verpoest, Wim Veraverbeke, Jan Delcour

Priority date: 26/09/2002

This invention consists of a modified gluten biopolymer for use in industrial applications, such as composites and foams. In the present work, the fracture toughness of the gluten polymer was improved with the addition of a thiol-containing modifying agent. This work also resulted in the development of a gluten biopolymer-modified fibre bundle, demonstrating the potential to process fully biodegradable composite materials...

NANO-ENGINEERED COMPOSITES

The Composite Materials Group of KU Leuven entered quite late into the nano-field. A request by the Belgian company Nanocyl, producer of carbon nanotubes (CNT's), to use our composite processing equipment and composites testing knowhow, was at the origin of our research on nano-engineered composites. Having entered late in the field, where the addition of CNT's in polymers had already been extensively studied, we were able to immediately focus on the potential improvements of adding CNT's to fibre reinforced composites. The aim of these developments was to increase the damage tolerance of carbon and glass fibre reinforced composites by adding CNT's to the matrix and/or to the fibre matrix interface.

The best improvements were found when the CNT's were added to the sizing, which is applied to the fibres (glass or carbon) just after their production and before their impregnation with a matrix. This innovation was patented by Nanocyl, with KU Leuven researchers Ashish Warrier, Ajay Godara, Ignaas Verpoest and Stepan Lomov as co-inventors. Nanocyl commercialized this sizing, and the collaboration between KU Leuven and Nanocyl in developing and evaluating new CNT-solutions for nano-engineered composites continues untill to today.

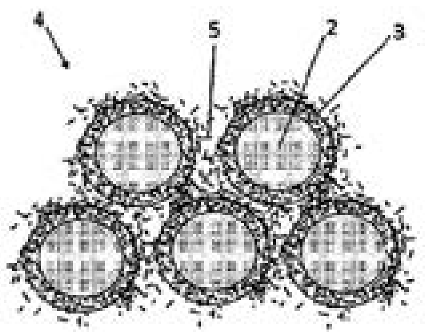
WO2010007163

Method For The Preparation Of A Reinforced Thermoset Polymer Composite

Inventors: Ignaas Verpoest, Stepan Lomov, Ashish Warrier and Ajay Godara (KU Leuven); Luca Mezzo, Olivier Rochez and Frederic Luizi (Nanocyl)

Priority date: 17/07/2008

The present invention refers to a method for the preparation of a reinforced thermoset polymer composite, said thermoset polymer composite comprising coated fibres, the coating being used as a vehicle for the introduction of carbon nanotubes into the thermoset polymer...



CONCLUSION

The Composite Materials Group at KU Leuven has gone a long way since the early, and disappointing, experience of not having patented its very first invention. Gradually, with the help of KU Leuven's tech-transfer office LRD, a portfolio of 15 patents in 6 different areas of polymer and composites science has been created. These days, innovative ideas are almost systematically screened based on their patentability. Several new patent applications are under preparation, and filed patents are being further elaborated.

Was this all worth the effort? Certainly, but it was not easy! Evaluating whether an innovation is patentable is a delicate task, writing a strong patent requires experience and professionalism, exploiting a patent requires skills other than just scientific excellence. Our track record looks good: one third of the patents are now being exploited in concrete applications, another third are on the way to being licensed or evaluated as the starting point of a spin-off company, and a final third did not, for various reasons, make it to industrial reality. Moreover, some of our research results, generated in the framework of direct collaborations with industry, have been used by companies to file their own patents; these patents are not included in this overview.

The most important outcome of our patent policy, however, might be that we have created an attitude within a group of young researchers, that their innovative ideas are worth protecting, and that such protection does not hinder the development of an excellent scientific record in terms of publications. While publications have sometimes been slightly delayed, they never have been made impossible. Patents are just another way of sharing your innovations, giving it back to the society that funded your research.

PUBLICATIONS

JOURNAL PAPERS

Wevers M., Verpoest I., Aernoudt E., and De Meester P., *Analysis of fatigue damage in CFR epoxy composites by means of acoustic emission: setting up a damage accumulation theory,* Journal of acoustic emission, *1985, vol. 4, issue 2-3, p. 186-190*

Verpoest I. and Springer G.S., *Effects of Moisture on the Compressive and Interlaminar Shear Strengths of Aramid-Epoxy Composites,* Journal of Reinforced Plastics and Composites, *1988, vol. 7, issue 1, p. 23-32*

Verpoest I. and Springer G.S., *Moisture Absorption Characteristics of Aramid-Epoxy Composites,* Journal of Reinforced Plastics and Composites, *1988, vol. 7, issue 1, p. 2-22*

Verpoest I., Wevers M., Demeester P., and Declercq P., *2.5D-fabrics and 3D-fabrics for delamination resistant composite laminates and sandwich structures,* Sampe journal, *1989, vol. 25, issue 3, p. 51-56*

Wevers M., Verpoest I., and De Meester P., *Identification of fatigue failure modes in carbon fibre reinforced composites with the energy discriminating acoustic emission method,* Journal of acoustic emission, *1989, vol. 8, issue 1-2, p. 272-276*

Doxsee L.E., Janssens W., Verpoest I., and Demeester P., *Strength of Aramid-Epoxy Composites during Moisture Absorption,* Journal of Reinforced Plastics and Composites, *1991, vol. 10, issue 6, p. 645-655*

Davies P., Kausch H.H., Williams J.G., Kinloch A.J., Charalambides M.N., Pavan A., Moore D.R., Prediger R., Robinson I., Burgoyne N., Friedrich K., Wittich H., Rebelo C.A., Torres Marques A., Ramsteiner F., Melve B., Fischer M., Roux N., Martin D., Czarnocki P., Neville D., Verpoest I., Goffaux B., Lee R., Walls K., Trigwell N., Partridge I.K., Jaussaud J., Andersen S., Giraud Y., Hale G., and McGrath G., *Round-robin interlaminar fracture testing of carbon-fibre-reinforced epoxy and PEEK composites,* Composites Science and Technology, *1992, vol. 43, issue 2, p. 129-136*

Ivens J., Van Vuure A.W., and Verpoest I., *Textiel voor composieten, een "oude" technologie voor een modern constructiemateriaal,* Het ingenieursblad, *1992, vol. 61, issue 12, p. 20-32*

Lacroix T., Tilmans B., Keunings R., Desaeger M., and Verpoest I., *Modelling of critical fibre length and interfacial debonding in the fragmentation testing of polymer composites,* Composites Science and Technology, *1992, vol. 43, issue 4, p. 379-387*

Verpoest I., Wevers M., Rubbrecht P., Rutten G., Ivens J., Desaeger M., and Verhoyen A., *Algemene inleiding tot de vezelversterkte kunstoffen,* Productietechniek, *1992, vol. 58, issue 7-8, p. 233-251*

Desaeger M. and Verpoest I., *On the use of the micro-indentation test technique to measure the interfacial shear strength of fibre-reinforced polymer composites,* Composites Science and Technology, *1993, vol. 48, issue 1, p. 215-226*

Doxsee L.E., Rubbrecht P., Li L., Verpoest I., and Scholle M., *Delamination Growth in Composite Plates Subjected to Transverse Loads,* Journal of Composite Materials, *1993, vol. 27, issue 8, p. 764-781*

Pitkethly M.J., Favre J.P., Gaur U., Jakubowski J., Mudrich S.F., Caldwell D.L., Drzal L.T., Nardin M., Wagner H.D., Di Landro L., Hampe A., Armistead J.P., Desaeger M., and Verpoest I., *A round-robin programme on interfacial test methods,* Composites Science and Technology, *1993, vol. 48, issue 1, p. 205-214*

Verpoest I., Desaeger M., Ivens J., and Wevers M., *Interfaces in Polymer Matrix Composites - from Micromechanical Tests to Macromechanical Properties,* Makromolekulare Chemie-Macromolecular Symposia, *1993, issue 75, p. 85-98*

Ivens J., Debaere P., Mcgoldrick C., Verpoest I., and Vandervleuten P., *2.5d Fabrics for Delamination Resistant Composite Structures,* Composites, *1994, vol. 25, issue 2, p. 139-146*

Ivens J., Wevers M., and Verpoest I., *Influence of Carbon-Fibre Surface-Treatment on Composite Ud Strength,* Composites, *1994, vol.25, issue 7, p. 722-728*

Lammerant L. and Verpoest I., *The interaction between matrix cracks and delaminations during quasi-static impact of composites,* Composites Science and Technology, *1994, vol. 51, issue 4, p. 505-516*

Albertsen H., Ivens J., Peters P., Wevers M., and Verpoest I., *Interlaminar fracture toughness of CFRP influenced by fibre surface treatment: Part 1. Experimental results,* Composites Science and Technology, *1995, vol. 54, issue 2, p. 133-145*

Ivens J., Albertsen H., Wevers M., Verpoest I., and Peters P., *Interlaminar fracture toughness of CFRP influenced by fibre surface treatment: Part 2. Modelling of the interface effect,* Composites Science and Technology, *1995, vol.54, issue 2, p. 147-159*

Lacroix T., Keunings R., Desaeger M., and Verpoest I., *A new data reduction scheme for the fragmentation testing of polymer composites,* Journal of Materials Science, *1995, vol. 30, issue 3, p. 683-692*

Morii T., Hamada H., Desaeger M., Gotoh A., Yokoyama A., Verpoest I., and Maekawa Z., *Damage Tolerance of Glass Mat/Epoxy Laminates Hybridized with Flexible Resin under Static and Impact Loading,* Composite Structures, *1995, vol. 32, issue 1-4, p. 133-139*

Van Vuure A.W., Ivens J., and Verpoest I., *Textiele vezelarchitecturen voor kunststof composieten,* Kunststof en Rubber, *1995, vol. 11, p. 13-17*

Desaeger M., Reis M.J., doRego A.M.B., daSilva J.D.L., and Verpoest I., *Surface characterization of poly(acrylonitrile) based intermediate modulus carbon fibres,* Journal of Materials Science, *1996, vol. 31, issue 23, p. 6305-6315*

Gommers B., Verpoest I., and Van Houtte P., *Further developments in testing and analysis of the plate twist test for in-plane shear modulus measurements,* Composites Part A, *1996, vol. 27, issue 11, p. 1085-1087*

Gommers B., Verpoest I., and Van Houtte P., *Modelling the elastic properties of knitted-fabric-reinforced composites,* Composites Science and Technology, *1996, vol. 56, issue 6, p. 685-694*

Lammerant L. and Verpoest I., *Modelling of the interaction between matrix cracks and delaminations during impact of composite plates,* Composites Science and Technology, *1996, vol. 56, issue 10, p. 1171-1178*

Vandeurzen P., Ivens J., and Verpoest I., *Structure-performance analysis of two-dimensional woven fabric composites,* Polymers & Polymer Composites, *1996, vol. 4, issue 5, p. 361-367*

Vandeurzen P., Ivens J., and Verpoest I., *A three-dimensional micromechanical analysis of woven-fabric composites: I. Geometric analysis,* Composites Science and Technology, *1996, vol. 56, issue v11, p. 1303-1315*

Vandeurzen P., Ivens J., and Verpoest I., *A three-dimensional micromechanical analysis of woven-fabric composites: II. Elastic analysis,* Composites Science and Technology, *1996, vol. 56, issue 11, p. 1317-1327*

Huysmans G., Marsol J.-F., Verpoest I., De Roeck G., De Ridder L., and Vansant J., *A field-friendly rigid composite coupler for GRP pipes,* Composite Structures, *1997, vol. 37, issue 2, p. 155-164*

Huysmans G. and Verpoest I., *Gebruik van vlakke breisels in composietmaterialen,* VezelVerSterkt, *1997, issue 1, p. 4-7*

Vandeurzen P., Ivens J., and Verpoest I., *Texcomp: A 3D analysis tool for 2D woven fabric composites,* Sampe Journal, *1997, vol. 33, issue 2, p. 25-33*

Vandeurzen P., Ivens J., and Verpoest I., *Micro-stress analysis in woven fabric composites using variational principles,* Plastics, rubber, and composites processing and applications, *1997, vol. 26, issue 10, p. 438-446*

Wu W., Desaeger M., Verpoest I., and Varna J., *An improved analysis of the stresses in a single-fibre fragmentation test: I. Two-phase model,* Composites Science and Technology, *1997, vol. 57, issue 7, p. 809-819*

Gommers B., Verpoest I., and Houtte P., *Analysis of knitted fabric reinforced composites: Part II. Stiffness and strength,* Composites Part A, *1998, vol. 29, issue 12, p. 1589-1601*

Gommers B., Verpoest I., and Van Houtte P., *Determination of the mechanical properties of composite materials by tensile tests. Part I: Elastic properties,* Journal of Composite Materials, *1998, vol. 32, issue 4, p. 310-334*

Gommers B., Verpoest I., and Van Houtte P., *The Mori–Tanaka method applied to textile composite materials,* Acta Materialia, *1998, vol. 46, issue 6, p. 2223-2235*

Gommers B., Verpoest I., and Van Houtte P., *Determination of the mechanical properties of composite materials by tensile tests. Part II: Strength properties,* Journal of Composite Materials, *1998, vol. 32, issue 2, p. 102-122*

Gommers B., Verpoest I., and Van Houtte P., *Analysis of knitted fabric reinforced composites: Part I. Fibre orientation distribution,* Composites Part A, *1998, vol. 29, issue 12, p. 1579-1588*

Huysmans G., Verpoest I., and De Roeck G., *Structural analysis of GRP pipe couplers by using a fracture mechanical approach,* Composites Part B-Engineering, *1998, vol. 29, issue 4, p. 477-487*

Huysmans G., Verpoest I., and Van Houtte P., *A poly-inclusion approach for the elastic modelling of knitted fabric composites,* Acta Materialia, *1998, vol. 46, issue 9, p. 3003-3013*

Jacobs E. and Verpoest I., *Finite element modelling of damage development during longitudinal tensile loading of coated fibre composites,* Composites Part A: Applied Science and Manufacturing, *1998, vol. 29, issue 9-10, p. 1007-1012*

Judawisastra H., Ivens J., and Verpoest I., *The fatigue behaviour and damage development of 3D woven sandwich composites,* Composite Structures, *1998, vol. 43, issue 1, p. 35-45*

Kettle A.P., Jones F.R., Alexander M.R., Short R.D., Stollenwerk M., Zabold J., Michaeli W., Wu W., Jacobs E., and Verpoest I., *Experimental evaluation of the interphase region in carbon fibre composites with plasma polymerised coatings,* Composites Part A, *1998, vol. 29, issue 3, p. 241-250*

Stumpf H., Mäder E., Baeten S., Pisanikovski T., Zäh W., Eng K., Andersson C.H., Verpoest I., and Schulte K., *New thermoplastic composite preforms based on split-film warp-knitting,* Composites Part A, *1998, vol. 29, issue 12, p. 1511-1523*

Vandeurzen P., Ivens J., and Verpoest I., *Micro-stress analysis of woven fabric composites by multilevel decomposition,* Journal of Composite Materials, *1998, vol. 32, issue 7, p. 623-651*

Wu W., Verpoest I., and Varna J., *An improved analysis of the stresses in a single-fibre fragmentation test—II. 3-phase model,* Composites Science and Technology, *1998, vol. 58, issue 1, p. 41-50*

Wu W., Verpoest I., and Varna J., *A novel axisymmetric variational analysis of stress transfer into fibres through a partially debonded interface,* Composites Science and Technology, *1998, vol. 58, issue 12, p. 1863-1877*

Baeten S. and Verpoest I., *Optimisation of a GMT-based cold pressing technique for low cost textile reinforced thermoplastic composites,* Composites Part A, *1999, vol. 30, issue 5, p. 667-682*

George J. and Verpoest J.I.I., *Mechanical properties of flax fibre reinforced epoxy composites,* Angewandte Makromolekulare Chemie, *1999, vol. 272, p. 41-45*

Judawisastra H., Ivens J., and Verpoest I., *Determination of core shear properties of three-dimensional woven sandwich composites,* Plastics Rubber and Composites, *1999, vol. 28, issue 9, p. 452-457*

Luo Y. and Verpoest I., *Compressibility and relaxation of a new sandwich textile preform for liquid composite molding,* Polymer Composites, *1999, vol. 20, issue 2, p. 179-191*

Morii T., Ivens J., and Verpoest I., *Interfacial effects on the mechanical properties of glass/phenolic composites,* Advanced Composites Letters, *1999, vol. 8, issue 6, p. 295-301*

Wu W., Jacobs E., Verpoest I., and Varna J., *Variational approach to the stress-transfer problem through partially debonded interfaces in a three-phase composite,* Composites Science and Technology, *1999, vol. 59, issue 4, p. 519-535*

Lomov S.V., Gusakov A.V., Huysmans G., Prodromou A., and Verpoest I., *Textile geometry preprocessor for meso-mechanical models of woven composites,* Composites Science and Technology, *2000, vol. 60, issue 11, p. 2083-2095*

Lomov S.V., Truevtzev A.V., and Cassidy C., *A predictive model for the fabric-to-yarn bending stiffness ratio of a plain-woven set fabric,* Textile research journal, *2000, vol. 70, issue 12, p. 1088-1096*

Lomov S.V. and Verpoest I., *Compression of woven reinforcements: A mathematical model,* Journal of Reinforced Plastics and Composites, *2000, vol. 19, issue 16, p. 1329-1350*

van Vuure A.W., Ivens J.A., and Verpoest I., *Mechanical properties of composite panels based on woven sandwich-fabric preforms,* Composites Part A: Applied Science and Manufacturing, *2000, vol. 31, issue 7, p. 671-680*

van Vuure A.W., Pflug J., Ivens J.A., and Verpoest I., *Modelling the core properties of composite panels based on woven sandwich-fabric preforms,* Composites Science and Technology, *2000, vol. 60, issue 8, p. 1263-1276*

Wu W., Verpoest I., and Varna J., *Prediction of energy release rate due to the growth of an interface crack by variational analysis,* Composites Science and Technology, *2000, vol. 60, issue 3, p. 351-360*

Huysmans G., Verpoest I., and Van Houtte P., *A damage model for knitted fabric composites,* Composites Part A, *2001, vol. 32, issue 10, p. 1465-1475*

Lomov S.V., Huysmans G., Luo Y., Parnas R.S., Prodromou A., Verpoest I., and Phelan F.R., *Textile composites: modelling strategies,* Composites Part A, *2001, vol. 32, issue 10, p. 1379-1394*

Lomov S.V., Huysmans G., and Verpoest I., *Hierarchy of textile structures and architecture of fabric geometric models,* Textile Research Journal, *2001, vol. 71, issue 6, p. 534*

Lomov S.V. and Verpoest I., *WiseTex - Virtual textile software,* Unitex, *2001, issue 1, p. 45-47*
Lomov S.V. and Verpoest I., *WiseTex – Virtual Textile software,* Vlakna a Textil, *2001, issue 2, p. 135-140*

Luo Y., Verpoest I., Hoes K., Vanheule M., Sol H., and Cardon A., *Permeability measurement of textile reinforcements with several test fluids,* Composites Part A, *2001, vol. 32, issue 10, p. 1497-1504*

Pandita S.D., Huysmans G., Wevers M., and Verpoest I., *Tensile fatigue behaviour of glass plain-weave fabric composites in on- and off-axis directions,* Composites Part A, *2001, vol. 32, issue 10, p. 1533-1539*

Parnas R., Lomov S., Ivens J., and Verpoest I., *Special issue: TexComp 5,* Composites Part A, *2001, vol. 32, issue 10, p. 1377-1377*

Parnas R., Lomov S.V., Ivens J., and Verpoest I., *Guest editorial: TexComp 5,* Composites Part A, *2001, vol. 32, issue 10, p. 1377-1377*

van Vuure A.W., Verpoest I., and Ko F.K., *Sandwich-fabric panels as spacers in a constrained layer structural damping application,* Composites Part B, *2001, vol. 32, issue 1, p. 11-19*

Belov E.B., Lomov S.V., Truevtzev N.N., Bradshaw M.S., and Harwood R.J., *Study of yarn snarling. Part I: Critical parameters of snarling,* Journal of the Textile Institute, *2002, vol. 93, issue 4, p. 341-365*

Falconnet D., Bourban P.E., Pandita S., Månson J.A.E., and Verpoest I., *Fracture toughness of weft-knitted fabric composites,* Composites Part B, *2002, vol. 33, issue 8, p. 579-588*

Harwood R., Belov E.B., Lomov S.V., and Truevtsev N.N., *Study of yarn snarling. Part II: Mathematical modelling,* Journal of the Textile Institute, *2002, vol. 93, issue 1, p. 366-385*

Hoes K., Dinescu D., Sol H., Vanheule M., Parnas R.S., Luo Y., and Verpoest I., *New set-up for measurement of permeability properties of fibrous reinforcements for RTM,* Composites Part A, *2002, vol. 33, issue 7, p. 959-969*

Langelaan G., Delannay L., Verpoest I., and Van Houtte P., *Deconvolution of morphological texture from crystallographic texture data,* Journal of Applied Crystallography, *2002, vol. 35, p. 327-337*

Lomov S.V., Belov E.B., Bischoff T., Ghosh S.B., Truong Chi T., and Verpoest I., *Carbon composites based on multiaxial multiply stitched preforms. Part 1. Geometry of the preform,* Composites Part A, *2002, vol. 33, issue 9, p. 1171-1183*

Lomov S.V., Parnas R.S., Bandyopadhyay Ghosh S., Verpoest I., and Nakai A., *Experimental and Theoretical Characterization of the Geometry of Two-Dimensional Braided Fabrics,* Textile Research Journal, *2002, vol. 72, issue 8, p. 706-712*

Luo Y. and Verpoest I., *Biaxial tension and ultimate deformation of knitted fabric reinforcements,* Composites Part A, *2002, vol. 33, issue 2, p. 197-203*

Pandita S.D., Falconet D., and Verpoest I., *Impact properties of weft knitted fabric reinforced composites,* Composites Science and Technology, *2002, vol. 62, issue 7, p. 1113-1123*

Vandepitte D., Bratfisch P., Pflug J., Vangrimde B., Fan X.Y., and Verpoest I., *Honingraten via thermoplastisch procédé,* Het Ingenieursblad, *2002, vol. 5, p. 21-24*

Delerue J.F., Lomov S.V., Parnas R.S., Verpoest I., and Wevers M., *Pore network modeling of permeability for textile reinforcements,* Polymer composites, *2003, vol. 24, issue 3, p. 344-357*

Lomov S.V., Truong Chi T., Verpoest I., Peters T., roose D., Boisse P., and Gasser A., *Mathematical Modelling of Internal Geometry and Deformability of Woven Preforms,* International Journal of Forming Processes, *2003, vol. 6, issue 3-4, p. 413-442*

Lomov S.V., Verpoest I., Barburski M., and Laperre J., *Carbon composites based on multiaxial multiply stitched preforms. Part 2. KES-F characterisation of the deformability of the preforms at low loads,* Composites Part A, *2003, vol. 34, issue 4, p. 359-370*

Lomov S.V., Verpoest I., Peeters T., Roose D., and Zako M., *Nesting in textile laminates: geometrical modelling of the laminate,* Composites Science and Technology, *2003, vol. 63, issue 7, p. 993-1007*

Pandita S.D., Nishiyabu K., and Verpoest I., *Strain concentrations in woven fabric composites with holes,* Composite Structures, *2003, vol. 59, issue 3, p. 361-368*

Pandita S.D. and Verpoest I., *Prediction of the tensile stiffness of weft knitted fabric composites based on X-ray tomography images,* Composites Science and Technology, *2003, vol. 63, issue 2, p. 311-325*

Parnas R.S., Wevers M., and Verpoest I., *Using textile topography to analyze X-ray CT data of composite microstructure,* Polymer Composites, *2003, vol. 24, issue 2, p. 212-220*

Pflug J., Vangrimde B., Verpoest I., Bratfisch P., and Vandepitte D., *Honeycomb core materials: New concepts for continuous production,* Sampe Journal, *2003, vol. 39, issue 6, p. 22-30*

Van de Weyenberg I., Ivens J., De Coster A., Kino B., Baetens E., and Verpoest I., *Influence of processing and chemical treatment of flax fibres on their composites,* Composites Science and Technology, *2003, vol. 63, issue 9, p. 1241-1246*

Wambua P., Ivens J., and Verpoest I., *Natural fibres: can they replace glass in fibre reinforced plastics?,* Composites Science and Technology, *2003, vol. 63, issue 9, p. 1259-1264*

Belov E.B., Lomov S.V., Verpoest I., Peters T., Roose D., Parnas R.S., Hoes K., and Sol H., ***Modelling of permeability of textile reinforcements: lattice Boltzmann method,*** Composites Science and Technology, *2004, vol. 64, issue 7, p. 1069-1080*

Bogaert G., Goeman L., de Ridder D., Wevers M., Ivens J., and Schuermans A., ***The physical and antimicrobial effects of microwave heating and alcohol immersion on catheters that are reused for clean intermittent catheterisation,*** European urology, *2004, vol. 46, issue 5, p. 641-646*

Hoes K., Dinescu D., Sol H., Parnas R.S., and Lomov S., ***Study of nesting induced scatter of permeability values in layered reinforcement fabrics,*** Composites Part A, *2004, vol. 35, issue 12, p. 1407-1418*

Koltysheva N.G., Lomov S.V., and Truevtzev N.N., ***Abrasion resistance of cotton/flax fabrics: 3d computer simulations of fabric wear geometry,*** AUTEX Research Journal, *2004, vol. 4, issue 4, p. 182-186*

Pandita S.D. and Verpoest I., ***Tension-tension fatigue behaviour of knitted fabric composites,*** Composite Structures, *2004, vol. 64, issue 2, p. 199-209*

Summerscales J., Russell P.M., Lomov S., Verpoest I., and Parnas R.S., ***The fractal dimension of X-ray tomographic sections of a woven composite,*** Advanced Composites Letters, *2004, vol. 13, issue 2, p. 113-121*

Woerdeman D.L., Veraverbeke W.S., Parnas R.S., Johnson D., Delcour J.A., Verpoest I., and Plummer C.J.G., ***Designing new materials from wheat protein,*** Biomacromolecules, *2004, vol. 5, issue 4, p. 1262-9*

Desplentere F., Lomov S.V., Woerdeman D.L., Verpoest I., Wevers M., and Bogdanovich A., ***Micro-CT characterization of variability in 3D textile architecture,*** Composites Science and Technology, *2005, vol. 65, issue 13, p. 1920-1930*

Gorbatikh L., Lomov S., and Verpoest I., ***Elastic compliance of a partially debonded circular inhomogeneity,*** International Journal of Fracture, *2005, vol. 131, issue 3, p. 211-229*

Langelaan G., Deprez S., Verpoest I., and Van Houtte P., ***Determination of morphological textures of the fibres in composite materials made from textiles of carbon fibres,*** icotom 14: textures of materials, pts 1and 2, *2005, vol. 495-497, p. 1675-1680*

Lomov S.V., Barburski M., Stoilova T., Verpoest I., Akkerman R., Loendersloot R., and Thije R.H.W.T., ***Carbon composites based on multiaxial multiply stitched preforms. Part 3: Biaxial tension, picture frame and compression tests of the preforms,*** Composites Part A, *2005, vol. 36, issue 9, p. 1188-1206*

Lomov S.V., Bernal E., Ivanov D.S., Kondratiev S.V., and Verpoest I., ***Homogenisation of a sheared unit cell of textile composites: FEA and approximate inclusion model,*** Revue Européenne des Éléments Finis, *2005, vol. 14, issue 6, p. 709-728*

Parton H., Baets J., Lipnik P., Goderis B., Devaux J., and Verpoest I., ***Properties of poly(butylene terephthatlate) polymerized from cyclic oligomers and its composites,*** Polymer, *2005, vol. 46, issue 23, p. 9871-9880*

Parton H. and Verpoest I., ***In situ polymerization of thermoplastic composites based on cyclic oligomers,*** Polymer Composites, *2005, vol. 26, issue 1, p. 60-65*

Truong T.C., Vettori M., Lomov S., and Verpoest I., ***Carbon composites based on multi-axial multi-ply stitched preforms. Part 4. Mechanical properties of composites and damage observation,*** Composites Part A, *2005, vol. 36, issue 9, p. 1207-1221*

Verpoest I. and Lomov S.V., ***Virtual textile composites software WiseTex: Integration with micro-mechanical, permeability and structural analysis,*** Composites Science and Technology, *2005, vol. 65, issue 15, p. 2563-2574*

Wambua P., Pirlot M., Lomov S.V., and Verpoest I., ***Protection against secondary fragmentation from AP mines based on natural fibre composites,*** Journal of Mine Action *,2005, vol. 9, issue 1w, p. 95-98*

Delye H., Goffin J., Verschueren P., Vander Sloten J., Van der Perre G., Alaerts H., Verpoest I., and Berckmans D., ***Biomechanical properties of the superior sagittal sinus-bridging vein complex,*** Stapp car crash journal, *2006, vol. 50, p. 625-36*

Fan X., Verpoest I., and Vandepitte D., ***Finite element analysis of out-of-plane compressive properties of thermoplastic honeycomb,*** Journal of Sandwich Structures & Materials, *2006, vol. 8, issue 5, p. 437-458*

Koissin V., Ruopp A., Lomov S.V., Verpoest I., Witzel V., and Drechsler K., ***On-surface fibre-free zones and irregularity of piercing pattern in structurally stitched NCF preforms,*** Advanced Composites Letters, *2006, vol. 15, issue 3, p. 81-88*

Loendersloot R., Lomov S.V., Akkerman R., and Verpoest I., ***Carbon composites based on multiaxial multiply stitched preforms. Part V: geometry of sheared biaxial fabrics,*** Composites Part A, *2006, vol. 37, issue 1, p. 103-113*

Lomov S.V. and Verpoest I., ***Model of shear of woven fabric and parametric description of shear resistance of glass woven reinforcements,*** Composites Science and Technology, *2006, vol. 66, issue 7, p. 919-933*

Lomov S.V. and Verpoest I., ***WiseTex: Virtual reality and real-world prediction of structure and properties of textile polymer composites (in Russian),*** Tehnicheskiy Tekstil, *2006, vol. N6, p. 37-41*

Lomov S.V., Willems A., Verpoest I., Zhu Y., Barburski M., and Sotilova T., ***Picture frame test of woven composite reinforcements with a full-field strain registration,*** Textile Research Journal, *2006, vol. 76, issue 3, p. 243-252*

Morren G., Gu J., Sol H., Verleye B., and Lomov S., ***Stereolithography specimen to calibrate permeability measurements for RTM flow simulations,*** Advanced Composites Letters, *2006, vol. 15, issue 4, p. 119-125*

Pflug J. and Verpoest I., ***Sandwich materials selection charts,*** J. Sandw. Struct. Mater., *2006, vol. 8, issue 5, p. 407-421*

Rabet L., Scheppers J., Verpoest I., Pirlot M., Desmet B., Gilson L., and Pirard P., ***Development of low cost composite plates for humanitarian dernining operations,*** Journal de Physique IV, *2006, vol. 134, p. 1225-1230*

Van de Weyenberg I., Chi Truong T., Vangrimde B., and Verpoest I., ***Improving the properties of UD flax fibre reinforced composites by applying an alkaline fibre treatment,*** Composites Part A, *2006, vol. 37, issue 9, p. 1368-1376*

Bratfisch P., Vandepitte D., Pflug J., and Verpoest I., ***Development and validation of a continuous production concept for thermoplastic honeycomb,*** Journal of Sandwich Structures & Materials, *2007, vol. 9, issue 2, p. 113-122*

Delye H., Verschueren P., Depreitere B., Verpoest I., Berckmans D., Sloten J.V., Van der Perre G., and Goffin J., ***Biomechanics of frontal skull fracture,*** J. Neurotrauma, *2007, vol. 24, issue 10, p. 1576-1586*

Gorbatikh L., Ivanov D., Lomov S., and Verpoest I., ***On modelling of damage evolution in textile composites on meso-level via property degradation approach,*** Composites Part A, *2007, vol. 38, issue 12, p. 2433-2442*

Gorbatikh L., Lomov S., and Verpoest I., ***On stress intensity factors of multiple cracks at small distances in 2-D problems,*** International Journal of Fracture, *2007, vol. 143, issue 4, p. 377-384*

Kurashiki T., Nakai H., Hirosawa S., Imura M., Zako M., Verpoest I., and Lomov S., ***Mechanical behaviors for textile composites by FEM based on damage mechanics,*** Advances in Composite Materials and Structures, Pts 1 and 2, *2007, vol. 334-335, p. 257-260*

Lomov S.V., Ivanov D.S., Verpoest I., Zako M., Kurashiki T., Nakai H., and Hirosawa S., ***Meso-FE modelling of textile composites: Road map, data flow and algorithms,*** Composites Science and Technology, *2007, vol. 67, issue 9, p. 1870-1891*

Lomov S.V., Mikolanda T., Kosek M., and Verpoest I., ***Model of internal geometry of textile fabrics: Data structure and virtual reality implementation,*** Journal of the Textile Institute, *2007, vol. 98, issue 1, p. 1-13*

Rawal A., Lomov S., Ngo T., Verpoest I., and Vankerrebrouck J., ***Mechanical behavior of Thru-air bonded nonwoven structures,*** Textile Research Journal, *2007, vol. 77, issue 6, p. 417-431*

Tolosana N., Koissin V., Lomov S.V., Stuve J., Miravete A., and Gonzalez J., ***Measurements of yarn paths in 3D braids,*** Advanced Composites Letters, *2007, vol. 16, issue 5, p. 161-165*

Vallons K., Zong M., Lomov S.V., and Verpoest I., ***Carbon composites based on multi-axial multi-ply stitched preforms – Part 6. Fatigue behaviour at low loads: Stiffness degradation and damage development,*** Composites Part A, *2007, vol. 38, issue 7, p. 1633-1645*

Verschueren P., Delye H., Depreitere B., Van Lierde C., Haex B., Berckmans D., Verpoest I., Goffin J., Vander Sloten J., and Van der Perre G., ***A new test set-up for skull fracture characterisation,*** Journal of Biomechanics, *2007, vol. 40, issue 15, p. 3389-3396*

Wambua P., Hu H., and Verpoest I., ***Impact response of hemp/polypropylene based composites,*** The Kenya Journal of Mechanical Engineering, *2007, vol. 3, issue 1, p. 21-28*

Wambua P., Vangrimde B., Lomov S., and Verpoest I., ***The response of natural fibre composites to ballistic impact by fragment simulating projectiles,*** Composite Structures, *2007, vol. 77, issue 2, p. 232-240*

Baets J., Dutoit M., Devaux J., and Verpoest I., ***Toughening of glass fibre reinforced composites with a cyclic butylene terephthalate matrix by addition of polycaprolactone,*** Composites Part A, *2008, vol. 39, issue 1, p. 13-18*

Baets J., Godara A., Devaux J., and Verpoest I., ***Toughening of polymerized cyclic butylene terephthalate with carbon nanotubes for use in composites,*** Composites Part A, *2008, vol. 39, issue 11, p. 1756-1761*

Cao J., Akkerman R., Boisse P., Chen J., Cheng H.S., de Graaf E.F., Gorczyca J.L., Harrison P., Hivet G., Launay J., Lee W., Liu L., Lomov S.V., Long A., de Luycker E., Morestin F., Padvoiskis J., Peng X.Q., Sherwood J., Stoilova T., Tao X.M., Verpoest I., Willems A., Wiggers J., Yu T.X., and Zhu B., ***Characterization of mechanical behavior of woven fabrics: Experimental methods and benchmark results,*** Composites Part A, *2008, vol. 39, issue 6, p. 1037-1053*

De Bruyne G., Aerts J.M., Van der Perre G., Goffin J., Verpoest I., and Berckmans D., ***Spatial differences in sensible and latent heat losses under a bicycle helmet,*** Eur J Appl Physiol, *2008, vol. 104, issue 4, p. 719-26*

Ivanov D., ***Identification of damage initiation and development in textile composite materials using acoustic emission,*** Journal of acoustic emission, *2008, vol. 26, p. 240-246*

Kerckhofs G., Schrooten J., Van Cleynenbreugel T., Lomov S.V., and Wevers M., ***Validation of x-ray microfocus computed tomography as an imaging tool for porous structures,*** The Review of scientific instruments, *2008, vol. 79, issue 1, p. 013711*

Lomov S.V., Boisse P., Deluycker E., Morestin F., Vanclooster K., Vandepitte D., Verpoest I., and Willems A., ***Full-field strain measurements in textile deformability studies,*** Composites Part A, *2008, vol. 39, issue 8, p. 1232-1244*

Lomov S.V., Ivanov D.S., Truong T.C., Verpoest I., Baudry F., Vanden Bosche K., and Xie H., ***Experimental methodology of study of damage initiation and development in textile composites in uniaxial tensile test,*** Composites Science and Technology, *2008, vol. 68, issue 12, p. 2340-2349*

Lomov S.V., Ivanov D.S., Verpoest I., Zako M., Kurashiki T., Nakai H., Molimard J., and Vautrin A., ***Full-field strain measurements for validation of meso-FE analysis of textile composites,*** Composites Part A, *2008, vol. 39, issue 8, p. 1218-1231*

Macaluso C., Vandepitte D., and Verpoest I., ***Deepdrawing FE-simulations for thermoplastic sandwich structures,*** International Journal of Material Forming, *2008, vol. 1, issue S1, p. 907-910*

Mikhaluk D.S., Truong T.C., Borovkov A.I., Lomov S.V., and Verpoest I., ***Experimental observations and finite element modelling of damage initiation and evolution in carbon/epoxy non-crimp fabric composites,*** Engineering Fracture Mechanics, *2008, vol. 75, issue 9, p. 2751-2766*

Rawal A., Lomov S., and Verpoest I., ***An environmental scanning electron microscope study of a through-air bonded structure under tensile loading,*** Journal of the Textile Institute, *2008, vol. 99, issue 3, p. 235-241*

Truong T.C., Ivanov D.S., Klimshin D.V., Lomov S.V., and Verpoest I., ***Carbon composites based on multi-axial multi-ply stitched preforms. Part 7: Mechanical properties and damage observations in composites with sheared reinforcement,*** Composites Part A, *2008, vol. 39, issue 9, p. 1380-1393*

Vanclooster K., Lomov S.V., and Verpoest I., ***Investigation of interply shear in composite forming,*** International Journal of Material Forming, *2008, vol. 1, issue S1, p. 957-960*

Vanclooster K., Lomov S.V., and Verpoest I., ***Simulating and validating the draping of woven fibre reinforced polymers,*** International Journal of Material Forming, *2008, vol. 1, p. 961-964*

Verleye B., Croce R., Griebel M., Klitz M., Lomov S.V., Morren G., Sol H., Verpoest I., and Roose D., *Permeability of textile reinforcements: Simulation, influence of shear and validation,* Composites Science and Technology, 2008, vol. 68, issue 13, p. 2804-2810

Willems A., Lomov S.V., Verpoest I., and Vandepitte D., *Optical strain fields in shear and tensile testing of textile reinforcements,* Composites Science and Technology, 2008, vol. 68, issue 3, p. 807-819

Willems A., Lomov S.V., Verpoest I., Vandepitte D., Harrison P., and Yu W.R., *Forming simulation of a thermoplastic commingled woven textile on a double dome,* International Journal of Material Forming, 2008, vol. 1, p. 965-968

Duflou J.R., De Moor J., Verpoest I., and Dewulf W., *Environmental impact analysis of composite use in car manufacturing,* CIRP Annals - Manufacturing Technology, 2009, vol. 58, issue 1, p. 9-12

Fan X., Verpoest I., Pflug J., Vandepitte D., and Bratfisch P., *Investigation of Continuously Produced Thermoplastic Honeycomb Processing - Part II: Fusion Bonding,* Journal of Sandwich Structures & Materials, 2009, vol. 11, issue 2-3, p. 179-198

Fan X., Verpoest I., Pflug J., Vandepitte D., and Bratfisch P., *Investigation of Continuously Produced Thermoplastic Honeycomb Processing -- Part I: Thermoforming,* Journal of Sandwich Structures and Materials, 2009, vol. 11, issue 2-3, p. 151-178

Godara A., Mezzo L., Luizi F., Warrier A., Lomov S.V., van Vuure A.W., Gorbatikh L., Moldenaers P., and Verpoest I., *Influence of carbon nanotube reinforcement on the processing and the mechanical behaviour of carbon fibre/epoxy composites,* Carbon, 2009, vol. 47, issue 12, p. 2914-2923

Gommer F., Lomov S., Vandenbosche K., and Verpoest I., *Error Assessment in Permeability Measurement Using Radial Flow Method,* Advanced Composites Letters, 2009, vol. 18, issue 4, p. 123-130

Ivanov D., Ivanov S., Lomov S., and Verpoest I., *Strain mapping analysis of textile composites,* Optics and Lasers in Engineering, 2009, vol. 47, issue 3, p. 360-370

Ivanov D.S., Baudry F., Van Den Broucke B., Lomov S.V., Xie H., and Verpoest I., *Failure analysis of triaxial braided composite,* Composites Science and Technology, 2009, vol. 69, issue 9, p. 1372-1380

Ivanov D.S., Lomov S.V., Bogdanovich A.E., Karahan M., and Verpoest I., *A comparative study of tensile properties of non-crimp 3D orthogonal weave and multi-layer plain weave E-glass composites. Part 2: Comprehensive experimental results,* Composites Part A, 2009, vol. 40, issue 8, p. 1144-1157

Koissin V., Kustermans J., Lomov S.V., Verpoest I., Nakai H., Kurashiki T., Hamada K., Momoji Y., and Zako M., *Structurally stitched woven preforms: experimental characterisation, geometrical modelling, and FE analysis,* Plastics Rubber and Composites, 2009, vol. 38, issue 2-4, p. 98-105

Koissin V., Kustermans J., Lomov S.V., Verpoest I., Van Den Broucke B., and Witzel V., *Structurally stitched NCF preforms: Quasi-static response,* Composites Science and Technology, 2009, vol. 69, issue 15, p. 2701-2710

Lomov S.V., Bogdanovich A.E., Ivanov D.S., Mungalov D., Karahan M., and Verpoest I., *A comparative study of tensile properties of non-crimp 3D orthogonal weave and multi-layer plain weave E-glass composites. Part 1: Materials, methods and principal results,* Composites Part A, 2009, vol. 40, issue 8, p. 1134-1143

Lomov S.V., Godara A., and Warrier A., *Compressibility of a nanotube "forest",* Composites and Nanostructures, 2009, vol. 1, issue 1, p. 59-64
Morren G., Bottiglieri M., Bossuyt S., Sol H., Lecompte

D., Verleye B., and Lomov S.V., *A reference specimen for permeability measurements of fibrous reinforcements for RTM,* Composites Part A, 2009, vol. 40, issue 3, p. 244-250

Vallons K., Lomov S.V., and Verpoest I., *Fatigue and post-fatigue behaviour of carbon/epoxy non-crimp fabric composites,* Composites Part A, 2009, vol. 40, issue 3, p. 251-259

Van Acker K., Verpoest I., De Moor J., Duflou J.R., and Dewulf W., *Lightweight materials for the automotive: environmental impact analysis of the use of composites,* Revue de Métallurgie, 2009, vol. 106, issue 12, p. 541-546

Vanclooster K., Lomov S.V., and Verpoest I., *Experimental validation of forming simulations of fabric reinforced polymers using an unsymmetrical mould configuration,* Composites Part A, 2009, vol. 40, issue 4, p. 530-539

Vanclooster K., Van Goidsenhoven S., Lomov S.V., and Verpoest I., *Optimizing the Deepdrawing of Multilayered Woven Fabric Composites,* International Journal of Material Forming, 2009, vol. 2, p. 153-156

Willems A., Lomov S.V., Verpoest I., and Vandepitte D., *Drape-ability characterization of textile composite reinforcements using digital image correlation,* Optics and Lasers in Engineering, 2009, vol. 47, issue 3, p. 343-351

Asiminei A.G., Depreitere B., Vander Sloten J., Verpoest I., and Goffin J., *In vivo evaluation of brain motion and deformation patterns by Magnetic Resonance Imaging and relation with cerebral contusion etiology,* World Neurosurgery, 2010, vol. 1

Baets J., Devaux J., and Verpoest I., *Toughening of Basalt Fibre-Reinforced Composites with a Cyclic Butylene Terephthalate Matrix by a Nonisothermal Production Method,* Advances in Polymer Technology, 2010, vol. 29, issue 2, p. 70-79

Baets J., Godara A., Devaux J., and Verpoest I., *Toughening of isothermally polymerized cyclic butylene terephthalate for use in composites,* Polymer Degradation and Stability, 2010, vol. 95, issue 3, p. 346-352

Carvelli V., Gramellini G., Lomov S.V., Bogdanovich A.E., Mungalov D.D., and Verpoest I., *Fatigue behavior of non-crimp 3D orthogonal weave and multi-layer plain weave E-glass reinforced composites,* Composites Science and Technology, 2010, vol. 70, issue 14, p. 2068-2076

Carvelli V., Tomaselli V.N., Lomov S.V., Verpoest I., Witzel V., and Broucke B.V.D., *Fatigue and post-fatigue tensile behaviour of non-crimp stitched and unstitched carbon/epoxy composites,* Composites Science and Technology, 2010, vol. 70, issue 15, p. 2216-2224

Daggumati S., De Baere I., Van Paepegem W., Degrieck J., Xu J., Lomov S.V., and Verpoest I., *Local damage in a 5-harness satin weave composite under static tension: Part I – Experimental analysis,* Composites Science and Technology, 2010, vol. 70, issue 13, p. 1926-1933

Daggumati S., Van Paepegem W., Degrieck J., Xu J., Lomov S.V., and Verpoest I., *Local damage in a 5-harness satin weave composite under static tension: Part II – Meso-FE modelling,* Composites Science and Technology, 2010, vol. 70, issue 13, p. 1934-1941

De Bruyne G., Aerts J.-M., Sloten J.V., Goffin J., Verpoest I., and Berckmans D., *Transient sweat response of the human head during cycling,* International Journal of Industrial Ergonomics, 2010, vol. 40, issue 4, p. 406-413

Defoirdt N., Biswas S., De Vriese L., Tran L.Q.N., Van Acker J., Ahsan Q., Gorbatikh L., Van Vuure A., and Verpoest I., *Assessment of the tensile properties of coir, bamboo and jute fibre,* Composites Part A, 2010, vol. 41, issue 5, p. 588-595

Godara A., Gorbatikh L., Kalinka G., Warrier A., Rochez O., Mezzo L., Luizi F., van Vuure A.W., Lomov S.V., and Verpoest I., *Interfacial shear strength of a glass fibre/epoxy bonding in composites modified with carbon nanotubes,* Composites Science and Technology, 2010, vol. 70, issue 9, p. 1346-1352

Gorbatikh L., Lomov S.V., and Verpoest I., *Original mechanism of failure initiation revealed through modelling of naturally occurring microstructures,* Journal of the Mechanics and Physics of Solids, 2010, vol. 58, issue 5, p. 735-750

Gorbatikh L., Lomov S.V., and Verpoest I., *Relation Between Elastic Properties and Stress Intensity Factors for Composites with Rigid-Line Reinforcements,* International Journal of Fracture, 2010, vol. 161, issue 2, p. 205-212

Ivanov D.S., Lomov S.V., Ivanov S.G., and Verpoest I., *Stress distribution in outer and inner plies of textile laminates and novel boundary conditions for unit cell analysis,* Composites Part A, 2010, vol. 41, issue 4, p. 571-580

Karahan M., Lomov S.V., Bogdanovich A.E., Mungalov D., and Verpoest I., *Internal geometry evaluation of non-crimp 3D orthogonal woven carbon fabric composite,* Composites Part A, 2010, vol. 41, issue 9, p. 1301-1311

Lomov S.V., Koissin V., Karahan M., Godara A., Gorbatikh L., and Verpoest I., *Compressibility of Cnt-Grafted Fibrous Reinforcements: A Theory,* International Journal of Material Forming, 2010, vol. 3, p. 627-630

Rawal A., Lomov S., and Verpoest I., *Theory of Fibre Contacts and their Applications to the Properties of Nonwoven Structures,* International Journal of Nonlinear Sciences and Numerical Simulation, 2010, vol. 11, issue 1, p. 57-62

Rawal A., Priyadarshi A., Kumar N., Lomov S.V., and Verpoest I., *Tensile behaviour of nonwoven structures: comparison with experimental results,* J. Mater. Sci., 2010, vol. 45, issue 24, p. 6643-6652

Rawal A., Priyadarshi A., Lomov S.V., Verpoest I., and Vankerrebrouck J., *Tensile behaviour of thermally bonded nonwoven structures: model description,* Journal of Materials Science, 2010, vol. 45, issue 9, p. 2274-2284

Sargent J., Chen J., Sherwood J., Cao J., Boisse P., Willem A., Vanclooster K., Lomov S.V., Khan M., Mabrouki T., Fetfatsidis K., and Jauffres D., *Benchmark Study of Finite Element Models for Simulating the Thermostamping of Woven-Fabric Reinforced Composites.,* International Journal of Material Forming, 2010, vol. 3, issue 1, p. 683-686

Taketa I., Ustarroz J., Gorbatikh L., Lomov S.V., and Verpoest I., *Interply hybrid composites with carbon fibre reinforced polypropylene and self-reinforced polypropylene,* Composites Part A, 2010, vol. 41, issue 8, p. 927-932

Valizadeh M., Lomov S., Ravandi S.A.H., Salimi M., and Rad S.Z., *Finite Element Simulation of a Yarn Pullout Test for Plain Woven Fabrics,* Textile Research Journal, 2010, vol. 80, issue 10, p. 892-903

Vallons K., Behaeghe A., Lomov S.V., and Verpoest I., *Impact and post-impact properties of a carbon fibre non-crimp fabric and a twill weave composite,* Composites Part A: Applied Science and Manufacturing, 2010, vol. 41, issue 8, p. 1019-1026

Van Den Broucke B., Hamila N., Middendorf P., Lomov S.V., Boisse P., and Verpoest I., *Determination of the mechanical properties of textile-reinforced composites taking into account textile forming parameters,* International Journal of Material Forming, 2010, vol. 3,S issue 2, p. 1351-1361

Vanclooster K., Lomov S.V., and Verpoest I., *Simulation of Multi-Layered Composites Forming,* International Journal of Material Forming, 2010, vol. 3, p. 695-698

Vandeurzen P., Ivens J., and Verpoest I., *ChemInform Abstract: Mechanical Modeling of Solid Woven Fabric Composites,* ChemInform, 2010, vol. 32, issue 24,

Verleye B., Lomov S.V., Long A., Verpoest I., and Roose D., *Permeability prediction for the meso-macro coupling in the simulation of the impregnation stage of Resin Transfer Moulding,* Composites Part A, 2010, vol. 41, issue 1, p. 29-35

Warrier A., Godara A., Rochez O., Mezzo L., Luizi F., Gorbatikh L., Lomov S.V., VanVuure A.W., and Verpoest I., *The effect of adding carbon nanotubes to glass/epoxy composites in the fibre sizing and/or the matrix,* Composites Part A, 2010, vol. 41, issue 4, p. 532-538

Arbter R., Beraud J.M., Binetruy C., Bizet L., Bréard J., Comas-Cardona S., Demaria C., Endruweit A., Ermanni P., Gommer F., Hasanovic S., Henrat P., Klunker F., Laine B., Lavanchy S., Lomov S.V., Long A., Michaud V., Morren G., Ruiz E., Sol H., Trochu F., Verleye B., Wietgrefe M., Wu W., and Ziegmann G., *Experimental determination of the permeability of textiles: A benchmark exercise,* Composites Part A, 2011, vol. 42, issue 9, p. 1157-1168

Biswas S., Ahsan Q., Verpoest I., and Hasan M., *Effect of Span Length on the Tensile Properties of Natural Fibres,* Advances in Materials and Processing Technologies Ii, Pts 1 and 2, 2011, vol. 264-265, p. 445-450

Daggumati S., Van Paepegem W., Degrieck J., Praet T., Verhegghe B., Xu J., Lomov S.V., and Verpoest I., *Local strain in a 5-harness satin weave composite under static tension: Part II – Meso-FE analysis,* Composites Science and Technology, 2011, vol. 71, issue 9, p. 1217-1224

Daggumati S., Voet E., Van Paepegem W., Degrieck J., Xu J., Lomov S.V., and Verpoest I., *Local strain in a 5-harness satin weave composite under static tension: Part I – Experimental analysis,* Composites Science and Technology, 2011, vol. 71, issue 8, p. 1171-1179

De Greef N., Gorbatikh L., Godara A., Mezzo L., Lomov S.V., and Verpoest I., *The effect of carbon nanotubes on the damage development in carbon fibre/epoxy composites,* Carbon, 2011, vol. 49, issue 14, p. 4650-4664

De Greef N., Gorbatikh L., Lomov S.V., and Verpoest I., ***Damage development in woven carbon fibre/epoxy composites modified with carbon nanotubes under tension in the bias direction,*** Composites Part A, *2011, vol. 42, issue 11, p. 1635-1644*

Fuentes C.A., Tran L.Q.N., Dupont-Gillain C., Vanderlinden W., De Feyter S., Van Vuure A.W., and Verpoest I., ***Wetting behaviour and surface properties of technical bamboo fibres,*** Colloids and Surfaces a-Physicochemical and Engineering Aspects, *2011, vol. 380,v1-3, p. 89-99*

Ivanov D.S., Ivanov S.G., Lomov S.V., and Verpoest I., ***Unit cell modelling of textile laminates with arbitrary inter-ply shifts,*** Composites Science and Technology,*2011, vol. 72, issue 1, p. 14-20*

Ivens J., Urbanus M., and De Smet C., ***Shape recovery in a thermoset shape memory polymer and its fabric-reinforced composites,*** Express Polymer Letters, *2011, vol. 5, issue 3, p. 254-261*

Karahan M., Lomov S.V., Bogdanovich A. E., and Verpoest I., ***Fatigue tensile behavior of carbon/epoxy composite reinforced with non-crimp 3D orthogonal woven fabric,*** Composites Science and Technology,*2011, vol. 71, issue 16, p. 1961-1972*

Lambrighs K., Verpoest I., Verlinden B., and Wevers M., ***Influence of the load ratio on the threshold stress intensity factor range for heavily drawn steel wires,*** Engineering Failure Analysis, *2011, vol. 18, issue 2, p. 694-699*

Lambrighs K., Wevers M., Verlinden B., and Verpoest I., ***A fracture mechanics approach to fatigue of heavily drawn steel wires,*** Procedia Engineering, *2011, vol. 10, p. 3267-3274*

Lomov S., Moesen M., Stalmans R., Trzcinski G., Van Humbeeck J., and Verpoest I., ***Finite element modelling of SMA textiles: superelastic behaviour,*** Journal of The Textile Institute, *2011, vol. 102, issue 3, p. 232-247*

Lomov S.V., Gorbatikh L., Houlle M., Kotanjac Ž., Koissin V., Vallons K., and Verpoest I., ***Compression resistance and hysteresis of carbon fibre tows with grown carbon nanotubes/nanofibres,*** Composites Science and Technology, *2011, vol. 71, issue 15, p. 1746-1753*

Lomov S.V., Gorbatikh L., Kotanjac Ž., Koissin V., Houlle M., Rochez O., Karahan M., Mezzo L., and Verpoest I., ***Compressibility of carbon woven fabrics with carbon nanotubes/nanofibres grown on the fibres,*** Composites Science and Technology, *2011, vol. 71, issue 3, p. 315-325*

Lomov S.V., Gorbatikh L., and Verpoest I., ***Compression behaviour of a fibre bundle with grafted carbon nanotubes,*** Carbon, *2011, vol. 49, issue 13, p. 4458-4465*

Lomov S.V., Gorbatikh L., and Verpoest I., ***A model for the compression of a random assembly of carbon nanotubes,*** Carbon, *2011, vol. 49, issue 6, p. 2079-2091*

Lomov S.V., Perie G., Ivanov D.S., Verpoest I., and Marsal D., ***Modeling three-dimensional fabrics and three-dimensional reinforced composites: challenges and solutions,*** Textile Research Journal, *2011, vol. 81, issue 1, p. 28-41*

Osorio L., Trujillo E., Van Vuure A.W., and Verpoest I., ***Morphological aspects and mechanical properties of single bamboo fibres and flexural characterization of bamboo/epoxy composites,*** Journal of Reinforced Plastics and Composites,*2011, vol. 30, issue 5, p. 396-408*

Prodromou A.G., Lomov S.V., and Verpoest I., ***The method of cells and the mechanical properties of textile composites,*** Composite Structures, *2011, vol. 93, issue 4, p. 1290-1299*

Tran L.Q.N., Fuentes C.A., Dupont-Gillain C., Van Vuure A.W., and Verpoest I., ***Wetting analysis and surface characterisation of coir fibres used as reinforcement for composites,*** Colloids and Surfaces a-Physicochemical and Engineering Aspects, *2011, vol. 377, issue 1-3, p. 251-260*

Vallons K., Duque I., Lomov S.V., and Verpoest I., ***Loading direction dependence of the tensile stiffness, strength and fatigue life of biaxial carbon/epoxy NCF composites,*** Composites Part A, *2011, vol. 42, issue 1, p. 16-21*

Alam K., Kerckhofs G., Mitrofanov A.V., Lomov S., Wevers M., and Silberschmidt V.V., ***On-line analysis of cracking in cortical bone under wedge penetration,*** Proc. Inst. Mech. Eng. Part H-J. Eng. Med., *2012, vol. 226, issue 9, p. 709-717*

Bocsan I.A., Conradi M., Zorko M., Jerman I., Hancu L., Borzan M., Fabre M., and Ivens J., ***Shape-Memory Polymers Filled with Sio2 Nanoparticles,*** Materiali in Tehnologije, *2012, vol. 46, issue 3, p. 243-246*

Carvelli V., Pazmino J., Lomov S.V., Bogdanovich A.E., Mungalov D.D., and Verpoest I., ***Quasi-static and fatigue tensile behavior of a 3D rotary braided carbon/epoxy composite,*** Journal of Composite Materials, *2012*

Carvelli V., Pazmino J., Lomov S.V., and Verpoest I., ***Deformability of a non-crimp 3D orthogonal weave E-glass composite reinforcement,*** Composites Science and Technology, *2012, vol. 73, p. 9-18*

De Bruyne G., Aerts J.-M., Vander Sloten J., Goffin J., Verpoest I., and Berckmans D., ***Quantification of local ventilation efficiency under bicycle helmets,*** International Journal of Industrial Ergonomics, *2012, vol. 42, issue 3, p. 278-286*

Fuentes C.A., Tran L.Q.N., Dupont-Gillain C., Van Vuure A.W., and Verpoest I., ***Interfaces in Natural Fibre Composites: Effect of Surface Energy and Physical Adhesion,*** Journal of Biobased Materials and Bioenergy, *2012, vol. 6, issue 4, p. 456-462*

Hossain R.M., Islam A., Van Vuure A.W., and Ignaas V., ***Effect of Fibre Orientation on the Tensile Properties of Jute Epoxy Laminated Composite,*** Journal of Scientific Research, *2012, vol. 5, issue 1, p. 43-54*

Jain A., Verpoest I., Hack M., Lomov S.V., Adam L., and Van Paepegem W., ***Fatigue life simulation on fibre reinforced composites - Overview and methods of analysis for the automotive industry,*** SAE International Journal of Materials & Manufacturing, *2012, vol. 5, issue 1, p. 205-214*

Karahan M., Gul H., Ivens J., and Karahan N., ***Low velocity impact characteristics of 3D integrated core sandwich composites,*** Textile Research Journal, *2012, vol. 82, issue 9, p. 945-962*

Karahan M., Karahan N., Gul H., and Ivens J., ***Quasi-static behavior of three-dimensional integrated core sandwich composites under compression loading,*** Journal of Reinforced Plastics and Composites, *2012, vol. 32, issue 5, p. 289-299*

Monea A.G., Verpoest I., Vander Sloten J., Van der Perre G., Goffin J., and Depreitere B., ***Assessment of Relative Brain-Skull Motion in Quasistatic Circumstances by Magnetic Resonance Imaging,*** J. Neurotrauma, *2012, vol. 29, issue 13, p. 2305-2317*

Olave M., Vanaerschot A., Lomov S.V., and Vandepitte D., ***Internal geometry variability of two woven composites and related variability of the stiffness,*** Polymer Composites, *2012, vol. 33, issue 8, p. 1335-1350*

Vanaerschot A., Cox B., Lomov S.V., and Vandepitte D., ***Stochastic framework for quantifying the geometrical variability of laminated textile composites using micro-computed tomography,*** Composites Part A, *2012, vol. 44, p. 122-131*

Vanclooster K., Barburski M., Lomov S.V., and Verpoest I., ***Experimental characterization of steel fibre knitted fabrics deformability,*** Experimental Mechanics, *2012*

Appermont R., Van Mieghem B., Van Bael B., Vanhove H., Duflou J., and Ivens J., ***Sneller thermovormen met minder energie! Metaalplaatgebaseerde matrijzen voor lagedrukvormgevingstechnieken van kunststoffen en composieten,*** Visie op Kunststof, *2013, vol. 3, issue 4, p. 26-27*

Conradi M., Zorko M., Jerman I., Orel B., and Verpoest I., ***Optimizing the performance of silica/polyvinyl chloride composites,*** Plastics research online, *2013*

Conradi M., Zorko M., Jerman I., Orel B., and Verpoest I., ***Mechanical properties of high density packed silica/poly(vinyl chloride) composites,*** Polymer Engineering & Science,*2013, vol. 53, issue 7, p. 1448-1453*

Conradi M., Zorko M., Kocijan A., and Verpoest I., ***Mechanical properties of epoxy composites reinforced with a low volume fraction of nanosilica fillers,*** Materials Chemistry and Physics, *2013, vol. 137, issue 3, p. 910-915*

Daggumati S., De Baere I., Van Paepegem W., Degrieck J., Xu J., Lomov S.V., and Verpoest I., ***Fatigue and post-fatigue stress–strain analysis of a 5-harness satin weave carbon fibre reinforced composite,*** Composites Science and Technology, *2013, vol. 74, p. 20-27*

Fuentes C.A., Tran L.Q.N., Van Hellemont M., Janssens V., Dupont-Gillain C., Van Vuure A.W., and Verpoest I., ***Effect of physical adhesion on mechanical behaviour of bamboo fibre reinforced thermoplastic composites,*** Colloids and Surfaces a-Physicochemical and Engineering Aspects, *2013, vol. 418, p. 7-15*

Jansens K.J.A., Hong N.V., Telen L., Brijs K., Lagrain B., Van Vuure A.W., Van Acker K., Verpoest I., Van Puyvelde P., Goderis B., Smet M., and Delcour J.A., ***Effect of molding conditions and moisture content on the mechanical properties of compression molded glassy, wheat gluten bioplastics,*** Industrial Crops and Products, *2013, vol. 44, p. 480-487*

Karahan M., Gul H., Karahan N., and Ivens J., ***Static behavior of three-dimensional integrated core sandwich composites subjected to three-point bending,*** Journal of Reinforced Plastics and Composites, *2013, vol. 32, issue 9, p. 664-678*

Lomov S.V., Verpoest I., Cichosz J., Hahn C., Ivanov D.S., and Verleye B., ***Meso-level textile composites simulations: Open data exchange and scripting,*** Journal of Composite Materials, *2013*

Barburski M., Lomov S.V., Lanckmans F., De Ridder F., and Verpoest I., ***Experimental study of steel and glass knitted fabrics thickness under pre-strain and shear,*** Key Engineering Materials, *2013, vol. 554-557, p. 385-390*

Phillips S., Baets J., Lessard L., Hubert P., and Verpoest I., ***Characterization of flax/epoxy prepregs before and after cure,*** Journal of Reinforced Plastics and Composites,*2013, vol. 32, issue 11, p. 777-785*

Swolfs Y., Crauwels L., Gorbatikh L., and Verpoest I., ***The influence of weave architecture on the mechanical properties of self-reinforced polypropylene,*** Composites Part A: Applied Science and Manufacturing, *2013, vol. 53, p. 129-136*

Swolfs Y., Gorbatikh L., Romanov V., Orlova S., Lomov S.V., and Verpoest I., ***Stress concentrations in an impregnated fibre bundle with random fibre packing,*** Composites Science and Technology, *2013, vol. 74, p. 113-120*

Swolfs Y., Gorbatikh L., and Verpoest I., ***Stress concentrations in hybrid unidirectional fibre-reinforced composites with random fibre packings,*** Composites Science and Technology, *2013, vol. 85, p. 10-16*

Tran L.Q.N., Fuentes C.A., Dupont-Gillain C., Van Vuure A.W., and Verpoest I., ***Understanding the interfacial compatibility and adhesion of natural coir fibre thermoplastic composites,*** Composites Science and Technology, *2013, vol. 80, p. 23-30*

Vallons K., Adolphs G., Lucas P., Lomov S.V., and Ignaas V., ***Quasi-UD glass fibre NCF composites for wind energy applications: a review of requirements and existing fatigue data for blade materials,*** Mechanics and Industry, *2013, vol. 14, issue 3, p. 175–189*

Vanaerschot A., Cox B.N., Lomov S.V., and Vandepitte D., ***Stochastic multi-scale modelling of textile composites based on internal geometry variability,*** Comput. Struct., *2013, vol. 122, p. 55-64*

BOOK CHAPTERS

Van Daele R., Verpoest I., and De Meester P., ***Detection of damage in composite materials using radiography,*** Manual on Experimental Guidelines for Testing Composites, 1989, SEM Composites Division, *p. 115-127*

Verpoest I., ***Interfacial board strength determination: fragmentation,*** Handbook of Polymer-fibre Composites,.1993, Longman Higher Education

Verpoest I., ***Interfacial board strength determination: review,*** Handbook of Polymer-fibre Composites, 1993, Longman Higher Education

Van Der Biest O., Lambrinou K., Lust P., Froyen L., Ivens J., and Verpoest I., ***Composite structural materials,*** Handbook of Microscopy: Applications in Materials Science, Solid State Physics and Chemistry, Chapter 12 , Amelinckx S., et al. Editors,1997

Vandeurzen P., Ivens J., and Verpoest I., ***Mechanical modelling of solid woven fabric composites,*** 3-D Textile Reinforcements in Composite Materials, 1999, Woodhead Publishing Limited, *p. 67-99*

Verpoest I., ***Composite preforming techniques,*** Comprehensive Composite Materials, Kelly A. and Zweben C. Editors, 2000, Elsevier, *p. 623-669*

De Roeck G. and Verpoest I., ***Ontwerpberekening voor Totem en realisatie van de kever / Design calculation for Totem and making of the beetle,*** Totem, Goedseels V. Editor, 2005, Mercatorfonds, *p. 23-26*

Lomov S.V., Verpoest I., and Robitaille F., *Manufacturing and internal geometry of textiles,* Design and manufacture of textile composites, Long A. Editor, 2005, Woodhead Publishing Ltd, *p. 1-60*

Boisse P., Akkerman R., Cao J., Chen J., Lomov S.V., and Long A., *Composites forming,* Advances in material forming. Esaform 10 years on, Chinesta F. and Cueto E. Editors, 2007, Springer, *p. 61-79*

Lomov S.V., *Virtual testing to establish material formability,* Composite Forming Technologies, Long A. Editor, 2007, Woodhead Publishing Ltd, *p. 80-116*

Verleye B., Klitz M., Croce R., Roose D., Lomov S.V., and Verpoest I., *Computation of permeability of textile with experimental validation for monofilament and non crimp fabrics,* Studies in Computational Intelligence (SCI), 2007, Springer Verlag, *Berlin-Heidelberg, p. 93-109*

Lomov S.V. and Verpoest I., *Textile composite materials: Polymer matrix composites,* Encyclopedia of Aerospace Engineering, Blockley R. and Shyy W. Editors, 2010, John Wiley& Sons, Ltd., *p. 2159-2176*

Ivanov D.S. and Lomov S.V., *Predicting the effect of stitching on the mechnaical properties and damage of non-crimp fabric composites: finite element analysis,* Non-crimp fabric composites: Manufacturing, properties and applications, Lomov S.V. Editor, 2011, Woodhead Publishing Ltd., *Cambridge, p. 360-385*

Lomov S.V., *Understanding and modeling the effect of stitching on the geometry of non-crimp fabrics,* Non-crimp fabric composites: Manufacturing, properties and applications, Lomov S.V. Editor, 2011, Woodhead Publishing Ltd., *Cambridge, p. 84-102*

Lomov S.V., *Deformability of textile preforms in the manufacture of non-crimp fabric composites,* Non-crimp fabric composites: Manufacturing, properties and applications, Lomov S.V. Editor, 2011, Woodhead Publishing Ltd., *Cambridge, p. 117-143*

Lomov S.V., Chi T.T., and Verpoest I., *Mechanical properties of non-crimp fabric (NCF) based composites: stiffness and strength,* Non-crimp fabric composites: Manufacturing, properties and applications, Lomov S.V. Editor, 2011, Woodhead Publishing Ltd., *Cambridge, p. 263-288*

Vallons K., *Fatigue in non-crimp fabric composites,* Non-crimp fabric composites: Manufacturing, properties and applications, Lomov S.V. Editor, 2011, Woodhead Publishing Ltd., *Cambridge*

Verleye B., Lomov S.V., and Roose D., *Modelling of the permeability of non-crimp fabrics for composites,* Non-crimp fabric composites: Manufacturing, properties and applications, Lomov S.V. Editor, 2011, Woodhead Publishing Ldt., *Cambridge,*

Baets J., *Semi-products with flax and hemp fibres,* Flax and Hemp fibres: a natural solution for the composite industry, Reux F. and Verpoest I. Editors, 2012, JEC Composites, *Paris, p. 87-98*

Baets J. and Lomov S.V., *Architecture of textile reinforcements and properties of composites,* Flax and Hemp fibres: a natural solution for the composite industry, Reux F. and Verpoest I. Editors, 2012, JEC Composites, *Paris, p. 61-70*

BOOKS

Verpoest I. and Wevers M., eds., *Proceedings of the European symposium on damage development and failure processes in composite materials : Leuven (Belgium), 4-5-6 May 1987,* 1987, KUL. departement metaalkunde en toegepaste materiaalkunde, *Heverlee*

Verpoest I. and Ko F.K., eds., *The Second International Symposium: TEXCOMP-2 : New Textiles for Composites: 17-19 May 1994.,* 1994, Katholieke Universiteit Leuven, *Leuven*

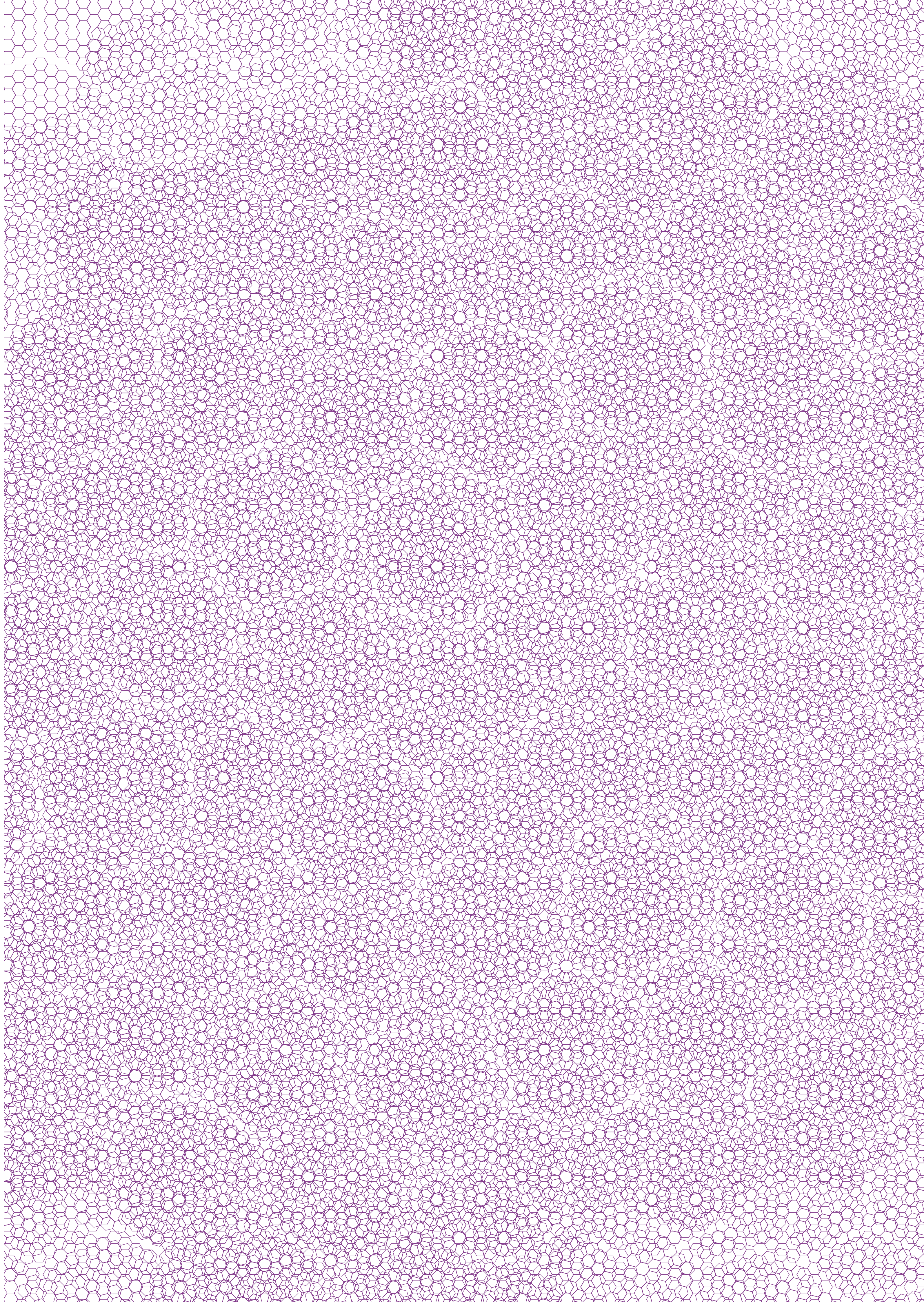
Derez M., De Roeck G., Verpoest I., De Baere B., Pil L., Baert B., Haerynck M., Van Loock F., Vekemans H., and Goedseels V., eds., *Totem, Jan Fabre : Mgr. Ladeuzeplein Leuven,* 2005, Mercatorfonds, *Antwerpen*

Pil L. and Verpoest I., eds., *Xtra strong / light composites,* 2006, Leuven university press, *Leuven*

Lomov S.V., ed., *Non-crimp fabric composites: Manufacturing, properties and applications,* 2011, Woodhead Publishing Ltd., *Cambridge*

Lomov SV, ed, *Non-crimp fabric composites: manufacturing, properties and applications,* 2011, Cambridge: Woodhead Publisher Ltd.

Reux F. and Verpoest I., eds., *Flax and Hemp fibres: a natural solution for the composite industry,* 2012, JEC Composites, *Paris*



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