

# Mechanical behaviour of « green » materials

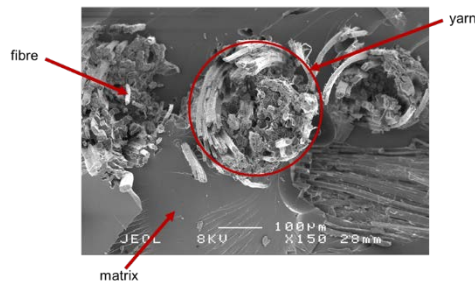
Fabienne Touchard, Laurence Chocinski-Arnault

with the help of technical staff and administrative services.

Contacts: [fabienne.touchard@ensma.fr](mailto:fabienne.touchard@ensma.fr), [laurence.chocinski@ensma.fr](mailto:laurence.chocinski@ensma.fr)

## Context

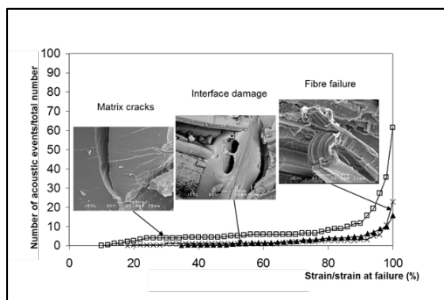
Global awareness of environmental issues has resulted in the emergence of “green” materials. These new materials offer eco-friendly and sustainable alternatives to classical ones, but their mechanical behaviour is not well known yet. The aim of this research topic is to analyse damage and strain mechanisms in recycled or bio-sourced polymers and in plant fibre composites, under different types of mechanical loading. For this purpose, multi-instrumented experimental tests are performed, at different scales of the studied materials. In particular, a specific attention is paid to the moisture influence, which is a key-point for plant fibre composite. Different techniques are adapted to these materials and compared : Digital Image Correlation (DIC), acoustic emission, X-ray micro-tomography, optical and scanning electron microscopies, infra-red thermography. Analytical and finite element modelling of the behaviour of these “green” materials are also performed and compared with experimental results.



Fracture surface of a woven hemp/epoxy composite.



Multi-instrumented mechanical test.



Damage analysis by Acoustic Emission and SEM observations.

## Studied materials

- ✓ Recycled or bio-sourced polymers.
- ✓ Plant fibre composites (hemp, flax, wood or straw reinforcement).
- ✓ Short fibres, medium fibres (non-woven mat), or continuous fibres (unidirectional ply or woven fabric).
- ✓ Hybrid composites (basalt-carbon, flax-carbon, flax-basalt).
- ✓ Thermoset or thermoplastic matrix.

## Analysis of damage, strain and failure mechanisms

- ✓ Fatigue and post-impact fatigue behaviour of hemp/epoxy composites.
- ✓ Determination of fatigue criterion for eco-composites.
- ✓ Tensile, fracture and impact behaviour of wood/PP, flax/PLA, hemp/epoxy composites.
- ✓ Full-field strain measurements by Digital Image Correlation (DIC) technique.
- ✓ Damage evolution analysis by coupling X-ray microtomography and acoustic emission methods.
- ✓ Material characterisation by using DSC, DMA, WAXS, optical and electron microscopies.
- ✓ Analytical and finite element modelling of eco-composite mechanical behaviour.
- ✓ Effect of stacking sequence, processing conditions, fibre quality, fibre length and ratio.
- ✓ Influence of ageing (thermal, moisture...) on tensile and fatigue properties.
- ✓ Properties of recycled polymers and recycled reinforced polymers.
- ✓ Comparison with classical composites (carbon and glass fibres).
- ✓ Analysis and optimization of fibre/matrix interface (see “Interfacial bonding quality at different scales in composite materials”).
- ✓ Numerical modelling.

## PhD students

- 2021-... : Samer El Khoury Roupheal, « Étude comparative et modélisation du comportement en fatigue après impact de stratifiés lin-époxy et verre-époxy. » (joint PhD with UQTR, Canada and ESTACA-Laval, France)
- 2020-... : Quentin Drouhet, « Étude multi-échelle des effets de la fatigue hydrique sur le comportement mécanique de composites à fibres végétales. »
- 2017-2020 : Romain Barbière, « Comportement en fatigue et optimisation de l'interface d'un composite tissé chanvre/époxy : effet de l'humidité. »
- 2016-2020 : Maria Carolina Seghini, « Damage and deformation mechanisms in basalt-plant fibre hybrid composites: role of interface optimization. » (joint PhD with La Sapienza, University of Roma, Italy)
- 2013 - 2016 : Amélie Perrier, « Etude expérimentale et numérique du comportement mécanique de l'interface renfort/matrice dans des éco-composites. »
- 2013 - 2016 : Yann Lebaupin, « Comportement mécanique à l'impact et en post-impact d'un éco-composite à base de fibres de lin associées à une matrice thermoplastique biosourcée. » (coll. ESTACA-LAVAL)
- 2010-2013 : Davi Vasconcellos, « Comportement en fatigue avant et après impact de composites tissés chanvre/époxy. » (with European Label)
- 2007-2010 : Claire Bonnafous, « Analyse multi-échelle des mécanismes d'endommagement de composites chanvre/époxy à renforts tissés. Caractérisation de l'interface fibre/matrice. »
- 2004-2007 : Olivier De Almeida, « Etude de l'influence de la présence d'impuretés sur les mécanismes de déformations et d'endommagements du polypropylène recyclé. Analyse des champs tridimensionnels de déformations. » (ADEME)
- 2001-2004 : Thuy Quynh Lam, « Qualification mécanique de composites à base de polymères recyclés et de fibres végétales. Caractérisation des mécanismes de rupture par imagerie numérique. » (ADEME)

## Programs and collaborations

- 2020-... : collaborative research and joint PhD (2021-...) on post-impact behaviour of flax composites with UQTR, Canada and ESTACA-Laval, France.
- 2020 : collaborative research and joint internship on flax/PP composites with Bcomp, Switzerland.
- 2019-... : collaborative research on hemp filaments with RBX Creations, France.
- 2018-2019 : PEPS CNRS "BioComp" on optimisation of interfacial bonding in eco-composites.
- 2019 : ACI PPRIME with IC2MP (Poitiers) on plasma treatment for hemp yarns.
- 2012-2020 : collaborative research and joint PhD (2016-2020) on mechanical behaviour of hybrid composites with Univ. La Sapienza (<http://www.uniroma1.it>), Roma, Italy.
- 2014-2018 : collaborative research on mechanical impact behaviour of eco-composites with IPCB (Institute for Polymers, Composites and Biomaterials - <http://www.ictmp.ct.cnr.it>), Napoli (Italy).
- 2014-2016 : program PICS CNRS n°6366 "ECAULT" : « Eco-Composites : damage Analysis Using Laser shock Technology » with IMP (Instytut Maszyn Przeplywowych - [www.imp.gda.pl/en/](http://www.imp.gda.pl/en/)) Gdansk, Poland, and PIMM-ParisTech.
- 2010-2011 : program ENSICHANVRE (MAPROSU CNRS) with Valagro, on the optimization of hemp fibre treatment.
- 2009-2012 : program BOREVE (ADEME) with Faurecia, MATEIS Lyon, LRMP St Etienne, IMFS-Strasbourg, FEMTO-Besançon, on material analysis for recycling the car bumpers.
- 2009-2010 : program Hemp Fibre (ACI PPRIME) with botanists of PhyMots-Univ. Poitiers, on influence of cultural conditions on mechanical properties of hemp fibres.
- 2007-2010 : program COMPOCHANVRE (Region) with CRITT Rochefort, Valagro, botanists of PhyMots-Univ. Poitiers, on mechanical behaviour of hemp/epoxy composite.
- 2005 : invited researcher Dr. Min Shen in 2005 from Univ of Tianjin (<http://www.tju.edu.cn/english/>) China, pursuing collaborative research on mechanical behaviour of wood polymer composites.
- 2004-2007 : program RECYPRO (ACI Ministère) on mechanical behaviour of recycled polymers with MATEIS Lyon, LRMP St Etienne, IMFS-Strasbourg, FEMTO-Besançon.

- 2002-2004 : program AGRICE (ADEME-CNRS) with Hutchinson, on flexural behaviour of hemp/glass/PU sandwich materials.
- 2000-2002 : program AGRICE (ADEME-CNRS) with Valagro, on microstructural and mechanical study of wood/PA composites.

## 25 papers in international journals (2015-2021):

1-A. PERRIER, D. VASCONCELLOS, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER,  
 "Full-field measurement at the weave scale in hemp/epoxy composite using digital image correlation." *Pol. & Pol. Comp.*, vol.23, n°9, pp.589-599, 2015.

2-A. PERRIER, R. ECAULT, F. TOUCHARD, M. VIDAL URRIZA, J. BAILLARGEAT, L. CHOCINSKI-ARNAULT, M. BOUSTIE,  
 "Towards the development of laser shock test for mechanical characterisation of fibre/matrix interface in eco-composite.", *Polymer Testing*, 44, pp. 125-134, 2015 (DOI: 10.1016/j.polymertesting.2015.04.003).

3-L. FERRANTE1, J. TIRILLO1, F. SARASINI1, F. TOUCHARD, R. ECAULT, M.A.VIDAL URRIZA, L. CHOCINSKI-ARNAULT, D. MELLIER,

1 : Sapienza Università di Roma, Italy.

"Behaviour of woven hybrid basalt-carbon/epoxy composites subjected to laser shock wave testing: preliminary results." *Composites Part B* 09/2015; 78(1) ; 162-173 (DOI:10.1016/j.compositesb.2015.03.084).

4-A. PERRIER, E. LE BOURHIS1, F. TOUCHARD, L. CHOCINSKI-ARNAULT,

1 : Axe SIMaC, PPRIME, France.

"Effect of water ageing on nanoindentation response of single hemp yarn/epoxy composites." *Comp. Part A*, 84, 216-223, 2016 (DOI: 10.1016/j.compositesa.2016.01.022).

5-F. SARASINI1, J. TIRILLÒ1, S. D'ALTILIA1, T. VALENTE1, C. SANTULLI2, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER, L. LAMPANI1, P. GAUDENZ1,

1 : Sapienza Università di Roma, Italy.

2 : Università di Camerino, Italy.

"Damage tolerance of carbon/flax hybrid composites subjected to low velocity impact.", *Comp. Part B*, 91, 144-153, 2016 (DOI: 10.1016/j.compositesb.2016.01.050).

6-Y. LEBaupin1, M. CHAUVIN1, T.Q. TRUONG HOANG1, F. TOUCHARD, A. BEIGBEDER2,

1 : ESTACA, Laval, France.

2 : CEMCAT, Changé, France.

"Influence of constituents and process parameters on mechanical properties of flax fibre reinforced polyamide 11 composite.", *J. of Thermoplastic Comp. Mat.*, pp.1-19, April 2016, DOI: 10.1177/0892705716644669.

7-A. PERRIER, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER,

"Mechanical behaviour analysis of the interface in single hemp yarn composites: DIC measurements and FEM calculations." *Pol. Testing*, 52, 1-8, 2016 (DOI:10.1016/j.polymertesting.2016.03.019).

8-F. TOUCHARD, M. BOUSTIE, L. CHOCINSKI-ARNAULT, P.P. GONZALEZ, L. BERTHE1, D.S. DE VASCONCELLOS2, L. SORRENTINO2, P.H. MALINOWSKI3, W. M. OSTACHOWICZ3,

1 : PIMM, CNRS-ENSAM Paristech, France.

2 : CNR, Portici (NA), Italy.

3 : IMP, Gdansk, Poland.

"Mechanical and laser impact effects on woven composites with hemp or glass fibres." *International Journal of Structural Integrity*, Vol. 8, Issue: 3, pp.286-307, 2017, <https://doi.org/10.1108/IJSI-06-2016-0022>.

9-A. PERRIER, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER,

"Influence of water on damage and mechanical behaviour of single hemp yarn composites." *Pol. Testing*, 57, 17-25, 2017, <http://dx.doi.org/10.1016/j.polymertesting.2016.10.035>.

10-L. SORRENTINO1, F. SARASINI2, J. TIRILLO2, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER, P. RUSSO1,

1 : CNR, Portici (NA), Italy.

2 : Sapienza Università di Roma, Italy.

"Damage Tolerance Assessment of the Interface Strength Gradation in Thermoplastic Composites." *Comp. Part B*, 113, pp.111-122, 2017. <http://dx.doi.org/10.1016/j.compositesb.2017.01.014>.

- 11-A. PERRIER, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER,  
“Quantitative analysis by micro-CT of damage during tensile test in a woven hemp/epoxy composite after water ageing.”  
Composites Part A, 102, pp18-27, 2017.  
DOI: 10.1016/j.compositesa.2017.07.018.
- 12-P.H. MALINOWSKI<sup>1</sup>, W. M. OSTACHOWICZ<sup>1</sup>, F. TOUCHARD, M. BOUSTIE, L. CHOCINSKI-ARNAULT, P.P. GONZALEZ, L. BERTHE<sup>2</sup>, D.S. DE VASCONCELLOS<sup>3</sup>, L. SORRENTINO<sup>3</sup>,  
1 : IMP, Gdansk, Poland.  
2 : PIMM, CNRS-ENSAM Paristech, France.  
3 : CNR, Portici (NA), Italy.  
“Study of plant fibre composites with damage induced by laser and mechanical impacts.” *Comp. Part B*, 152, 209-219, 2018, <https://doi.org/10.1016/j.compositesb.2018.07.004>.
- 13-M.C. SEGHINI, F. TOUCHARD, F. SARASINI<sup>1</sup>, L. CHOCINSKI-ARNAULT, D. MELLIER, J. TIRILLÒ<sup>1</sup>,  
1 : Sapienza Università di Roma, Italy.  
“Interfacial adhesion assessment in flax/epoxy and in flax/vinylester composites by single yarn fragmentation test: correlation with micro-CT analysis.”, *Comp. Part A*, 113, 66-75, 2018,  
<https://doi.org/10.1016/j.compositesa.2018.07.015>.
- 14-G. SIMEOLI<sup>1</sup>, L. SORRENTINO<sup>1</sup>, P. RUSSO<sup>1</sup>, F. TOUCHARD, D. MELLIER, M. OLIVIERO<sup>1</sup>  
1 : CNR, Portici (NA), Italy.  
“Comparison of falling dart and charpy impacts performances of compatibilized and not compatibilized polypropylene/woven glass fibres composites.” *Comp. Part B*, 165, pp.102-108, 2019,  
<https://doi.org/10.1016/j.compositesb.2018.11.090>.
- 15-B. FISCHER<sup>1</sup>, F. SARASINI<sup>2</sup>, J. TIRILLÒ<sup>2</sup>, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER, N. PANZER<sup>1</sup>, R. SOMMERHUBER<sup>1</sup>, P. RUSSO<sup>3</sup>, I. PAPA<sup>3</sup>, V. LOPRESTO<sup>3</sup>, R. ECAULT<sup>4</sup>,  
1 : XARION, Vienna, Austria.  
2 : Sapienza Università di Roma, Italy.  
3 : University of Naples, Italy.  
4 : AIRBUS, Toulouse, France.  
“Impact damage assessment in biocomposites by micro-CT and innovative air-coupled detection of laser-generated ultrasound.” *Composite Structures*, 210, pp.922-931, 2019, <https://doi.org/10.1016/j.compstruct.2018.12.013>.
- 16-Y. LEBaupin<sup>1</sup>, M. CHAUVIN<sup>1</sup>, T.Q. TRUONG HOANG<sup>1</sup>, F. TOUCHARD,  
1 : ESTACA, Laval, France.  
“Influence of the stacking sequence on the low-energy impact resistance of flax/PA11 composite.”, *J. of Comp. Mat.*, Vol. 53(22) 3187–3198, 2019, <https://doi.org/10.1177/0021998319837339>.
- 17-M.C. SEGHINI, F. TOUCHARD, F. SARASINI<sup>1</sup>, V. CECH<sup>2</sup>, L. CHOCINSKI-ARNAULT, D. MELLIER, J. TIRILLÒ<sup>1</sup>, M.P. BRACCIALE<sup>1</sup>, M. ZVONEK<sup>2</sup>,  
1 : Sapienza Università di Roma, Italy.  
2 : Brno University of Technology, Czech Republic.  
“Engineering the interfacial adhesion in basalt/epoxy composites by plasma polymerization.” *Comp Part A*, 122, 67-76, 2019, <https://doi.org/10.1016/j.compositesa.2019.04.013>.
- 18-M.C. SEGHINI, F. TOUCHARD, F. SARASINI<sup>1</sup>, L. CHOCINSKI-ARNAULT, J. TIRILLÒ<sup>1</sup>, M.P. BRACCIALE<sup>1</sup>, M. ZVONEK<sup>2</sup>, V. CECH<sup>2</sup>,  
1 : Sapienza Università di Roma, Italy.  
2 : Brno University of Technology, Czech Republic.  
“Effects of oxygen and tetravinylsilane plasma treatment on mechanical and interfacial properties of flax yarns in thermoset matrix composites.” *Cellulose*, 27, pp511–530, 2020. <https://doi.org/10.1007/s10570-019-02785-3>.
- 19-M.C. SEGHINI, F. TOUCHARD, L. CHOCINSKI-ARNAULT, V. PLACET<sup>1</sup>, C. FRANÇOIS<sup>1</sup>, L. PLASSERAUD<sup>1</sup>, M.P. BRACCIALE<sup>2</sup>, J. TIRILLÒ<sup>2</sup>, F. SARASINI<sup>2</sup>,  
1 : FEMTO-ST, Besançon, France.  
2 : Sapienza Università di Roma, Italy.  
“Environmentally friendly surface modification treatment of flax fibres by supercritical carbon dioxide.” *Molecules* 2020, 25, 438; pp1-16, doi:10.3390/molecules25030438.

- 20-R. BARBIÈRE, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER,  
“Influence of moisture and drying on fatigue damage mechanisms in a woven hemp/epoxy composite: acoustic emission and micro-CT analysis.” *Int. Journal of Fatigue*, 136 (2020) 105593. <https://doi.org/10.1016/j.ijfatigue.2020.105593>.
- 21-M.C. SEGHINI, J. TIRILLÒ1, M.P. BRACCIALE1, F. TOUCHARD, L. CHOCINSKI-ARNAULT, A. ZUORRO1, R. LAVECCHIA1, F. SARASINI1,  
1 : Sapienza Università di Roma, Italy.  
“Surface modification of flax yarns by enzymatic treatment and their interfacial adhesion with thermoset matrices.” *Applied Sciences*, 2020, 10, 2910; doi:10.3390/app10082910.
- 22-M.C. SEGHINI, F. TOUCHARD, F. SARASINI1, L. CHOCINSKI-ARNAULT, M.R. RICCIARDI2, V. ANTONUCCI2, J. TIRILLÒ1,  
1 : Sapienza Università di Roma, Italy.  
2 : IPCB, Portici,, Italy.  
“Fatigue behaviour of flax-basalt hybrid composites in comparison with non-hybrid composites.” *International journal of Fatigue* 2020, 139 (105800) pp.1-12.  
<https://doi.org/10.1016/j.ijfatigue.2020.105800>
- 23-F. SBARDELLA1, M. LILLI1, M.C. SEGHINI, I. BAVASSO1, F. TOUCHARD, L. CHOCINSKI-ARNAULT, I. RIVILLA2, J. TIRILLÒ1, F. SARASINI1,  
1 : Sapienza Università di Roma, Italy.  
2 : Donostia International Physics Center, San Sebastián, Spain.  
“Interface tailoring between flax yarns and epoxy matrix by ZnO nanorods.” *Composites Part A*, 140, 106156, 2021.  
<https://doi.org/10.1016/j.compositesa.2020.106156>
- 24- E. LE BOURHIS, F. TOUCHARD,  
Chapitre “Mechanical properties of natural fiber composites.” dans *Encyclopedia of Materials: Composites*, Ed. Elsevier, 2021 (14 pages). <https://doi.org/10.1016/B978-0-12-819724-0.00009-4>
- 25- R. BARBIÈRE, F. TOUCHARD, L. CHOCINSKI-ARNAULT, E. FOURRE1, E. LEROY2, J. BARRAULT2,  
1 : IC2MP, Poitiers, France.  
2 : Valagro, Poitiers, France.  
“Characterisation of interfacial adhesion in hemp composites after H2O2 and non thermal plasma treatments.” *J. of Composite Materials*, 2021, 1-12. <https://doi.org/10.1177/00219983211015427>.