Interfacial bonding quality at different scales in composite materials

Fabienne Touchard, Laurence Chocinski-Arnault, Michel Boustie

with the help of technical staff and administrative services.

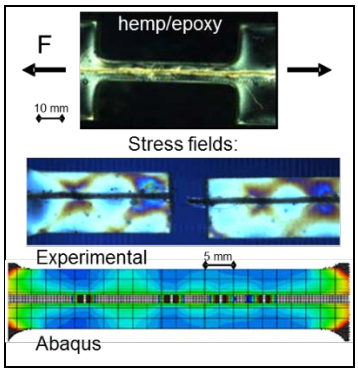
Contacts : fabienne.touchard@ensma.fr, laurence.chocinski@ensma.fr, michel.boustie@ensma.fr

Context

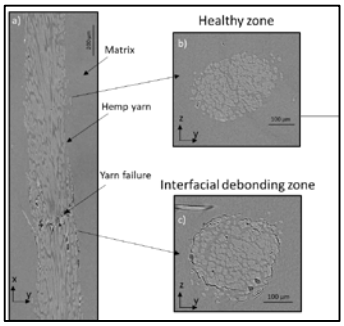
The properties and performances of a composite structure rely not only on its components but also on the bonding quality of its interfaces. Interfaces control the stress transfer from one part of the composite structure to the other, which depends on the adhesion level of the bonding. It is thus a key issue to determine and optimise the adhesion quality of interfaces. There are three different scales of interfaces in composite structures:

- at macro-scale, the bonding level at the interface between two composite laminates is a key-parameter that governs the whole structure integrity ;
- at meso-scale, the adhesion quality at interply in composite materials controls the delamination development ;
- at micro-scale, the fibre/matrix interface is a key-factor in the composite performances.

The aim of this thematic field is to analyse the interfacial properties in composite structures, and to test different ways of interfacial optimisation. Numerical simulations are also performed at the different scales and compared to multi-scale experimental measurements.



Fragmentation tests and simulation.



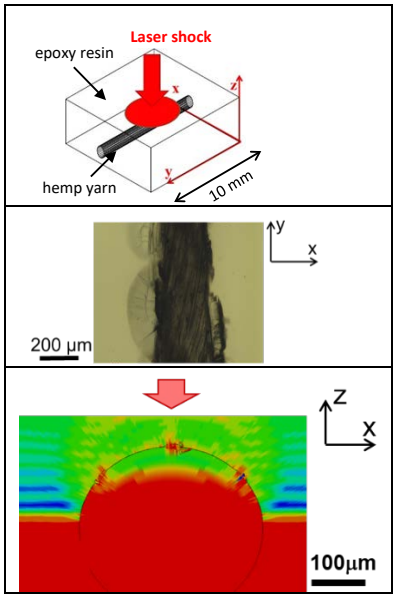
Micro-CT observations of a single hemp yarn-epoxy composite sample after fragmentation test

Research topics

- ✓ Measurements at the hemp yarn/polymer interface of the evolution of mechanical properties by using nanoindentation and Digital Image Correlation techniques.
- ✓ Determination of the yarn/matrix interface adhesion quality by means of laser shock technique and mechanical fragmentation tests.
- ✓ Realization of different surface treatments for natural fibre/matrix interface improvement: chemical, enzymatic and plasma treatments.
- ✓ Analysis of interfacial adhesion quality in 3D printed continuous carbon/nylon composites at filament/matrix and interlaminar scales.
- ✓ Development of a laser shock adhesion test for the assessment of weak adhesive bonded CFRP structures.
- ✓ Study of delamination threshold in hybrid composites.
- ✓ Test of new piezochromic coatings for impact detection.

Numerical simulations

- ✓ Numerical model for particles in polymer matrix. Application to EPDM/PP composites. Comparison of axisymmetric, 2D and 3D models. Study of cavitation phenomenon.



Laser shock tests on single hemp yarn embedded in epoxy resin.
Damage observation. Numerical simulation.

- ✓ Simulation of one short fibre in polymer matrix. Analysis of stress fields at fibre/matrix interface. Influence of fibre orientation.
- ✓ Finite element modelling of a single-yarn composite. Application to hemp/epoxy material. Comparison of numerical stress fields with photoelasticimetry results. Comparison of computed strain fields with Digital Image Correlation (DIC) measurements. Determination of model parameters by inverse analysis approach.
- ✓ Development of finite element models to predict the delamination in composite structures, taking into account the material microstructure.
- ✓ Modelling short fibre composites by creating a preprocessed program for random fibre elements generation. Application to wood/PP composites. Influence of fibre geometry and ratio. Comparison with tensile and fracture experimental tests.
- ✓ Simulation of woven composite material by using a simplified geometry definition, modelling warp and weft yarns, and by taking into account variability of fibre properties. Application to woven hemp/epoxy composite. Comparison of numerical and experimental damage evolution. Analysis of strain fields with DIC measurements at the weave scale.

PhD students

- 2021-… : Samer El Khoury Rouphael, « 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)
- 2015-2019 : Maxime Sagnard, dir. L. Berthe (PIMM-ParisTech) « Assemblage de matériaux composites carbone/polymère. Détection des joints faibles par des techniques de choc produit par laser. »
- 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 : Romain Ecault, dir. M. Boustie, « Développement du test d'adhérence d'assemblages composites collés par choc laser. »
- 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. »

Programs and collaborations

- 2020-… : collaborative research and joint PhD (2021-…) on post-impact behaviour of flax composites with UQTR, Canada and ESTACA-Laval, 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.
- 2015-2018 : European project H2020 ComBoNDT “Quality assurance concepts for adhesive bonding of aircraft composite structures by advanced NDT” Fraunhofer IFAM (Germany), AIRBUS (Germany, France), PIMM-ParisTech (France)…
- 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).
- 2014-2017 : ANR project ChoCoComp “Choc Detection by Innovative Reversible Piezochromic COatings for COMPosite Parts” with AIRBUS France.
- 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/) Gdansk, Poland, and PIMM-ParisTech.
- 2011-2014 : European project FP7 ENCOMB “Extended Non destructive testing for COMposite Bonds” with Fraunhofer IFAM (Germany), AIRBUS (Germany, France)…
- 2010-2011 : program ENSICHANVRE (MAPROSU CNRS) with Valagro, on the optimization of hemp fibre treatment.

27 papers in international journals (2015-2021):

1-R. ECAULT, L. BERTHE1, F. TOUCHARD, M. BOUSTIE, E. LESCOUTE2, A. SOLLIER2, H. VOILLAUME3,
1 : PIMM, CNRS-ENSAM Paristech, France.
2 : CEA-DIF, Arpajon, France.
3 : AIRBUS Group Innovation, Nantes, France.
"Experimental and numerical investigations of shock and shear waves propagation induced by femtosecond laser irradiation in epoxy resins.", J. Phys. D, 48, 2015 (doi:10.1088/0022-3727/48/9/095501).

2-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.

3-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).

4-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).

5-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).

6-F. SARASINI1, J. TIRILLÒ1, S. D’ALTILIA1, T. VALENTE1, C. SANTULLI2, F. TOUCHARD, L. CHOCINSKI-ARNAULT, D. MELLIER, L. LAMPANI1, P. GAUDENZI1,
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).

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-R. ECAULT1, F. TOUCHARD, M. BOUSTIE, L.BERTHE2, N. DOMINGUEZ1,
1 : AIRBUS Group Innovations, Toulouse, France.
2 : PIMM, CNRS-ENSAM Paristech, France.
“Numerical modeling of laser-induced shock experiments for the development of the adhesion test for bonded composite materials.” Composite Structures, 152, pp.382-394, 2016 (DOI: 10.1016/j.compstruct.2016.05.032).

9-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.

10-F GEHRING, M BOUSTIE, F TOUCHARD, L CHOCINSKI-ARNAULT, S GUINARD1, S. SENANI2,
1 : AIRBUS Group Innovations, Toulouse, France.
2 : AIRBUS Group Innovations, Suresnes, France.
“Use of laser shock waves to test new piezochromic coatings for impact detection.” Optical Engineering, 56(1):011023, 2017 (DOI: 10.1117/1.OE.56.1.011023).

11-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.

12-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.

13-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.

14-P.H. MALINOWSKI1, W. M. OSTACHOWICZ1, F. TOUCHARD, M. BOUSTIE, L. CHOCINSKI-ARNAULT, P.P. GONZALEZ, L. BERTHE2, D.S. DE VASCONCELLOS3, L. SORRENTINO3,
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.

15-M.C. SEGHINI, F. TOUCHARD, F. SARASINI1, L. CHOCINSKI-ARNAULT, D. MELLIER, J. TIRILLÒ1,
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.

16-M. SAGNARD1, R. ECAULT2, F. TOUCHARD, M. BOUSTIE, L.BERTHE1,
1 : PIMM, CNRS-ENSAM Paristech, France.
2 : AIRBUS Group Innovations, Toulouse, France.
"Development of the symmetrical laser shock test for weak bond inspection." Optics and Laser Technology 111, pp.644-652, 2019, https://doi.org/10.1016/j.optlastec.2018.10.052.

17-G. SIMEOLI1, L. SORRENTINO1, P. RUSSO1, F. TOUCHARD, D. MELLIER, M. OLIVIERO1
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.

18-Y. LEBAUPIN1, M. CHAUVIN1, T.Q. TRUONG HOANG1, 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.

19-M.C. SEGHINI, F. TOUCHARD, F. SARASINI1, V. CECH2, L. CHOCINSKI-ARNAULT, D. MELLIER, J. TIRILLÒ1, M.P. BRACCIALE1, M. ZVONEK2,
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.

20-M.C. SEGHINI, F. TOUCHARD, F. SARASINI1, L. CHOCINSKI-ARNAULT, J. TIRILLÒ1, M.P. BRACCIALE1, M. ZVONEK2, V. CECH2,
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.

21-M.C. SEGHINI, F. TOUCHARD, L. CHOCINSKI-ARNAULT, V. PLACET1, C. FRANÇOIS1, L. PLASSERAUD1, M.P. BRACCIALE2, J. TIRILLÒ2, F. SARASINI2,
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.

22-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.

23-R. ECAULT1, F. TOUCHARD, L.BERTHE2, M. BOUSTIE,
1 : AIRBUS Group Innovations, Toulouse, France.
2 : PIMM, CNRS-ENSAM Paristech, France.
"Laser Shock Adhesion Test numerical optimization for composite bonding assessment." Composite Structures, 2020. 112441, https://doi.org/10.1016/j.compstruct.2020.112441.

24-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

25-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

26-F. TOUCHARD, L. CHOCINSKI-ARNAULT, T. FOURNIER1, C. MAGRO1, A. LAFITTE, A. CARADEC,
1 : CANOE, Pessac, France.
"Interfacial adhesion quality in 3D printed continuous CF/PA6 composites at filament/matrix and interlaminar scales." Composites Part B, 218 (2021) 108891.
https://doi.org/10.1016/j.compositesb.2021.108891

27- 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.