Ageing and durability of organic matrix composites for aircraft applications

Marco GIGLIOTTI (Professor), Marianne BERINGHIER, Yannick PANNIER, Olga SMERDOVA (Associate Professors)

Contacts: marco.gigliotti@ensma.fr, marianne.beringhier@ensma.fr, yannick.pannier@ensma.fr, olga.smerdova@ensma.fr

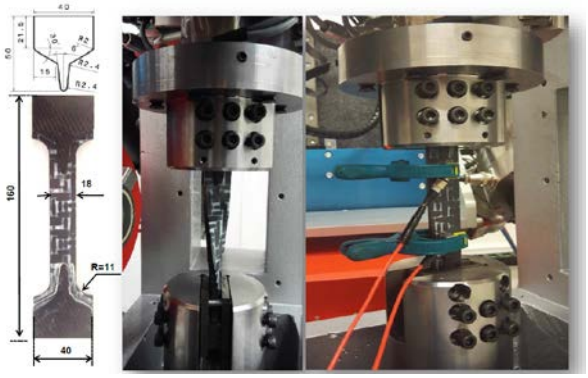
Post-doctoral researchers, PhD theses: Salvador ORENES BALACIART (MESR, 2020-2023), Julie MASSON (CIFRE SAFRAN Composites, 2020-2023), Maxime MERLE (FEDER HIC, 2019-2022), Manel DALLALI (Post-Doc EU ISIBHY, 2019-2021), Hortense LAUEFFER (Post-Doc EU HOMER, 2018-2020), Marina PECORA (Post-Doc SAFRAN Aircraft Engines, 2019), Ahmad AL TAKASH (LIU -ISAE ENSMA, 2015-2018), Anani DJATO (MESR, 2015-2018), Federico FOTI (Post-Doc SAFRAN Composites, 2017-2018), Yuriy SINCHUK (Post-Doc ANR LABEX, 2015-2017), Marina PECORA (MESR, 2015-2018), Federico FOTI (MESR, 2014-2017), Camille GUIGON (CIFRE SAFRAN, 2011-2014), Yueguo LIN (CSC, 2010-2013), Matteo MINERVINO (FUI COMPTINN', 2010-2013), Dinh Quy VU (MESR, 2008-2011), Loïc OLIVIER (ANR COMEDI, 2005-2008) N. Quang HO (MESR, 2003-2006), Sandrine ROUQUIE (RRIT SUPERSONIQUE, 2000-2003)

Partners: AIRBUS GROUP INNOVATIONS Suresnes, SAFRAN Group (SAFRAN Aircraft Engines, SAFRAN Composites, AIRCELLE), AIRBUS SAS Toulouse, ONERA, PIMM-ENSAM Paris, University of Versailles, LMT Cachan, KU Leuven (Belgium), Politecnico di Torino (Italy), Politecnico di Milano (Italy), University of Calabria (Italy), University of Padova (Italy)

Research programs: EU H2020 M-ERA.net ISIBHY (2019-2022), FEDER HIC (2019-2022), EU H2020-MG-2016-2017 Mobility for Growth HOMER (2018-2021), ANR IMPEKKABLE (2015-2019), PRC Composites (2011-2014), FUI COMPTINN' (2010-2013), FNRAE VICOMTHE (2008-2010), ANR COMEDI (2005-2008), RRIT SUPERSONIQUE (2000-2004)

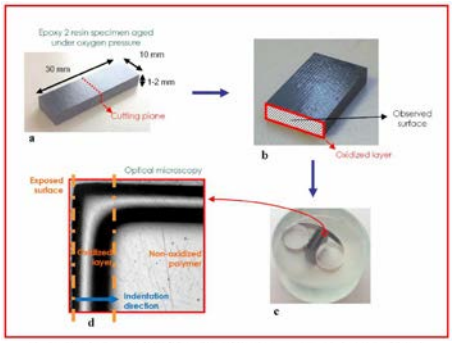
Experimental tools: Ultra-micro indentation, Optical and Interferometric microscopy, SEM, X-ray micro-tomography, In-situ micro-tomography, In-house experimental devices for mechanical testing under controlled environment (temperature, humid, neutral or oxidative)

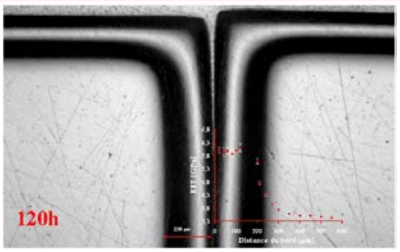
Context: The aim of this operation is to characterise the effect of thermo-oxidation on the behaviour (constitutive law, damage onset and propagation) of organic matrix composites for aircraft applications, in view of building predictive models, which can be useful for design and optimisation of structures. This aim is carried out by building and developing specific experimental test (coupled, uncoupled, multi-scale …) and by interpreting them by the aid of dedicated multi-physical/multi-scale models based on the Thermodynamics of Irreversible Processes. The models are implemented into commercial finite element software (such as, for instance, ABAQUS) or solved by dedicated numerical methods/schemes, such as the Proper Generalised Decomposition technique.

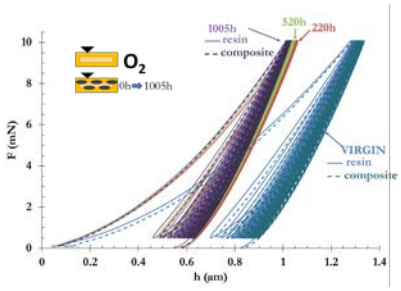


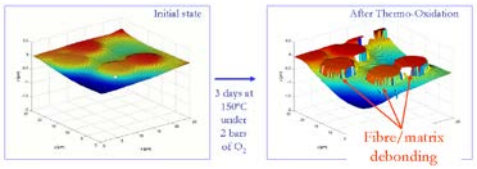
In-situ test of composite materials with complex texture

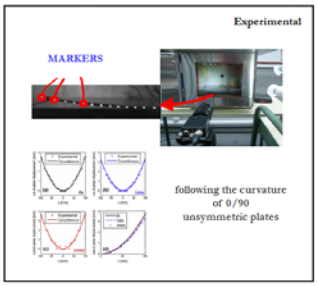
- ✓ Damage onset and propagation
- ✓ Damage morphology
- ✓ Temperature control

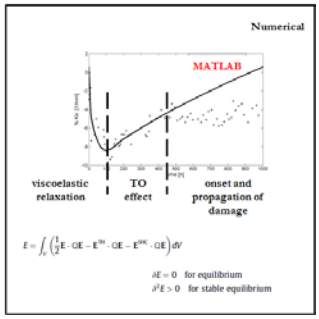






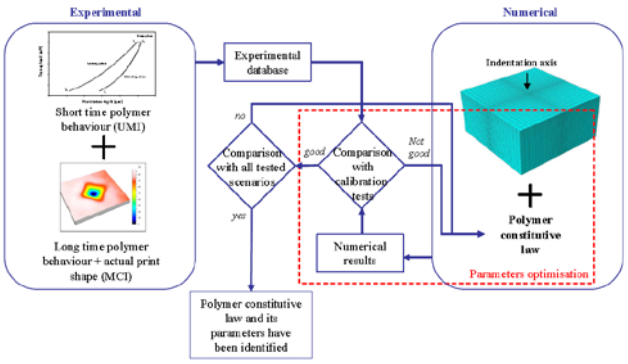


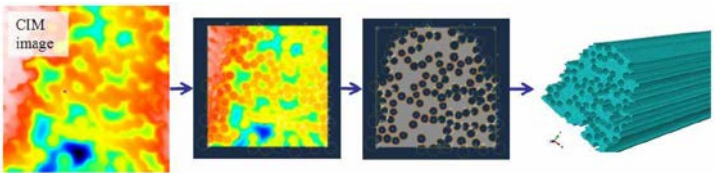


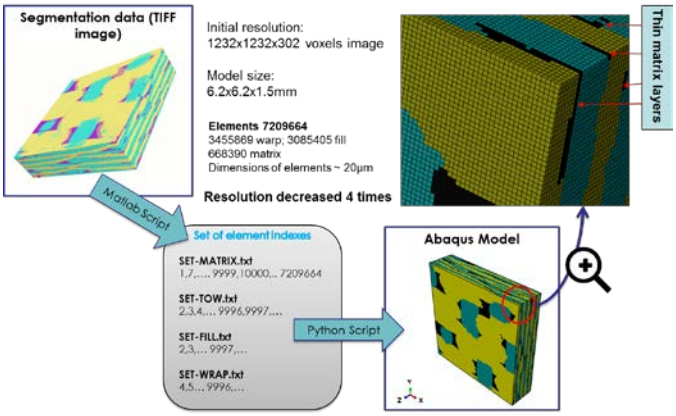


Characterisation of the effects of thermo-oxidation on the mechanical behaviour of OMC

- ✓ Coupled approach employing ultra-micro indentation and interferometric microscopy for the characterisation of the local constitutive law of virgin and aged resin samples
- ✓ Development of cyclic nanoindentation tests at high temperature for better understanding of ageing behaviour of polymers and polymer composites
- ✓ Interferometric microscopy observation of thermo-oxidation induced matrix shrinkage and damage onset in composites at the microscopic scale
- ✓ Traction tests on model [0/90]s virgin and aged samples
- ✓ Employment of model [0/90] unsymmetrical samples for on-line monitoring of thermo-oxidation in composite laminates
- ✓ Multi-physical fatigue at high temperature and under oxidizing environment (air, O_2) on laminated and textile composites

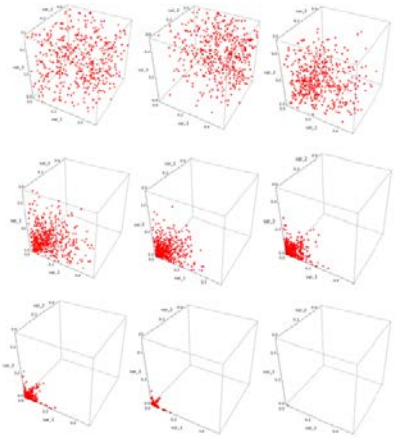






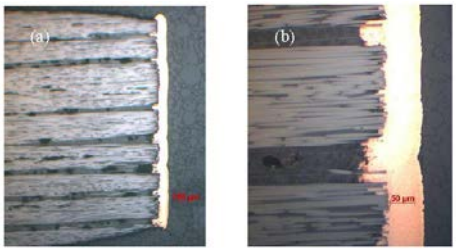
Modelling thermo-oxidation and its effects on the mechanical behaviour of OMC

- ✓ Employment of Thermodynamics of Irreversible Processes for the development of coupled multi-physics models
- ✓ Development of dedicated subroutines (UMAT/UEL) in the commercial finite element software ABAQUS for the simulation of thermo-oxidation in composites
- ✓ Development of reduced order methods (Proper Generalised Decomposition method) for simulation and identification of multi-physics couplings
- ✓ Development of FE models starting from micro-tomographic images: segmentation, meshing, analysis



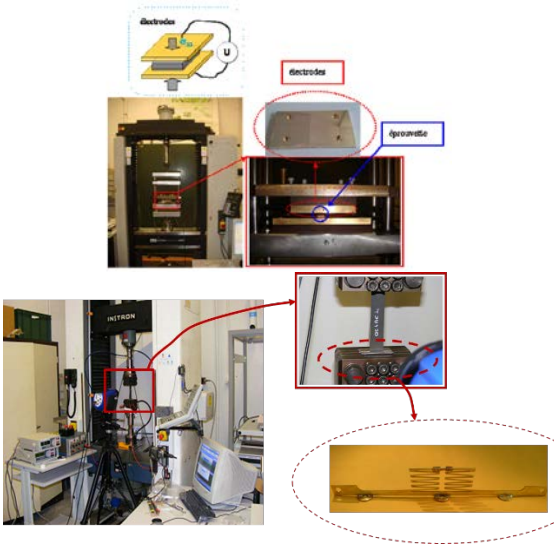
Identification of the thermo-diffusion—reaction-mechanical behaviour of composite materials

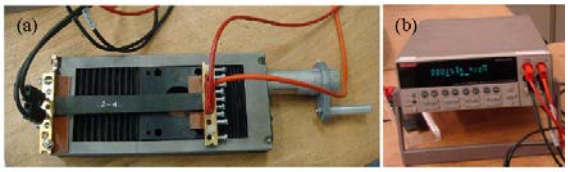
- ✓ Development of a PGD based identification method
- ✓ Employment of robust identification algorithms
- ✓ Employment of the slope method for gravimetric test identification over short conditioning times

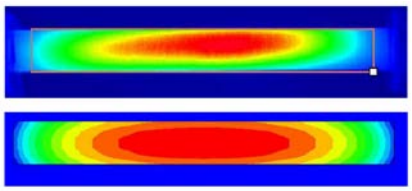


Characterisation of the thermoelectric behaviour of CFRP laminates and of the effects of electric currents on the mechanical behaviour of functional OMC

- ✓ Carbon fibers, epoxy matrix, carbon nanotubes
- ✓ Voltage/resistance/conductivity measurements
- ✓ Dedicated compression setup for the accurate measure of the through-the-thickness conductivity of OMC
- ✓ Electrical aging
- ✓ Electro-mechanical fatigue

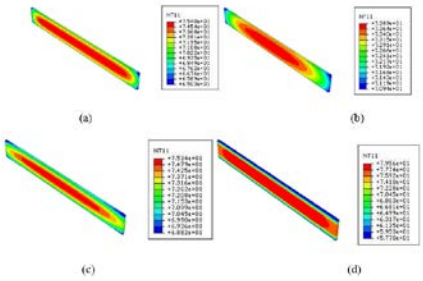


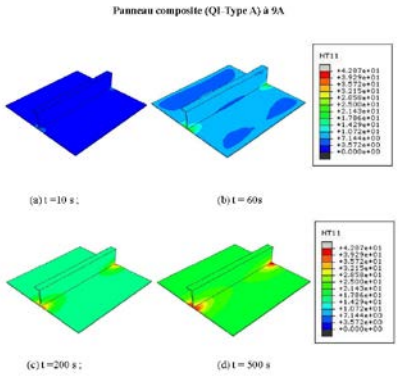




Modelling of thermo-electro-mechanical couplings

- ✓ Employment of Thermodynamics of Irreversible Processes for the development of coupled multi-physics models
- ✓ Development of dedicated subroutines (UMAT/UEL) in the commercial finite element software ABAQUS for the simulation of thermo-electro-mechanical coupling in composite materials





Publications:

- Foti, F., Pannier, Y. Orenes Balaciart, S.., Grandidier, J.C., Gigliotti, M. (2021) In-situ Multi-axial Testing of Three-dimensional (3D) Woven Organic Matrix Composites for Aeroengine Applications, Composite Structures, Accepted for publication.
- Pedoto, G., Smerdova, O., Grandidier, J.C., Gigliotti, M., Vinet, A. (2020) Characterization of the mechanical behavior of PEKK polymer and C/PEKK composite materials for aeronautical applications below and above the glass transition temperature, Advances in Aircraft & Spacecraft Science, Accepted for publication.
- Foti, F., Pannier, Y., Gigliotti, M. (2020) High Temperature Fatigue of Carbon/Polyimide 8-harness Satin Woven Composites. Part II: Environmental Effects, Composite Structures, 244, 112251.
- Pannier, Y., Foti, F., Gigliotti, M. (2020) High Temperature Fatigue of Carbon/Polyimide 8-harness Satin Woven Composites. Part I: Digital Image Correlation and Micro-Computed Tomography Damage Characterization, Composite Structures, 244, 112255.
- Severino, S., Gigliotti, M., Pannier, Y., Zappino, E., Pagani, A., Carrera, E. (2020) A Variable Kinematic One-dimensional Model for the Hygro-mechanical Analysis of Composite Materials, Composite Structures, 242, 112089.
- Beringhier, M., Gigliotti, M., Vannucci, P. (2020) Identification of Diffusion Properties of Polymer-Matrix Composite Materials with Complex Texture, Journal of Optimization Theory and Applications, 184: 188–209. – doi: https://doi.org/10.1007/s10957-019-01602-y
- Pecora, M., Smerdova, O., Gigliotti, M. (2020) In-situ Characterization of the Local Mechanical Behaviour of Polymer Matrix in 3D Carbon Fiber Composites by Cyclic Indentation Test, Composite Structures, 244, 112268.
- Djato, A., Beringhier, M., Gigliotti, M. (2020) On the identification of diffuso-mechanical properties of polymer matrix materials based on the use of plates with asymmetric moisture concentration field, Mechanics of Materials, 142: 103284. – doi: https://doi.org/10.1016/j.mechmat.2019.103284
- Al Takash, A., Beringhier, M., Hammoud, M., Grandidier J.C. (2020) A mixed PGD-a priori time basis strategy for the simulation of cyclic transient thermal behavior, Mechanics & Industry, 21, 606. https://doi.org/10.1051/meca/2020082
- Smerdova, O., Pecora, M., Gigliotti, M. (2019) Cyclic Indentation of Polymers: Instantaneous Elastic Modulus from Reloading, Energy Analysis, and Cyclic Creep, Journal of Materials Research, 34: 3688-369. – doi: https://doi.org/10.1557/jmr.2019.289
- Djato, A., Beringhier, M., Gigliotti, M. (2019) Identification of Moisture Affected Mechanical Properties of Polymer Matrix Materials by the Employment of Samples with Moisture Gradients, Mechanics of Advanced Materials and Structures, Accepted, In Press. - ISSN: 1537-6494
- Gigliotti, M. (2019) Thermodynamics of Irreversible Processes with Internal Variables: A Tool for Modeling Aging and Degradation Phenomena in Composite Materials for Aircraft Applications, Aerotec. Miss. Spaz., 98: 31-44. – ISSN: 0365-7442, doi:https://doi.org/10.1007/s42496-018-0002-z
- Lin, Y., Gigliotti, M., Lafarie-Frenot, M.C., Bai, J. (2019) Numerical Simulation of the Thermoelectric Behavior of CNTs/CFRP Composite Laminates for Aircraft Applications, Advances in Aircraft & Spacecraft Science, 5: 633-652. - doi: 10.12989/aas.2018.5.6.633
- Sinchuk, Y., Pannier, Y., Antoranz-Gonzalez, R., Gigliotti, M. (2019) Analysis of Moisture Diffusion Induced Stress in Carbon/Epoxy 3D Textile Composite Materials with Voids by μ-CT Based Finite Element Models, Composite Structures, 212: 561-570. - https://doi.org/10.1016/j.compstruct.2018.12.041
- Gigliotti, M., Pannier, Y., Sinchuk, Y., Antoranz-Gonzalez, R., Lafarie-Frenot, M.C., Lomov, S.V. (2018) X-ray Micro-Computed-Tomography Characterization of Cracks Induced by Thermal Cycling in Non-crimp 3D Orthogonal Woven Composite Materials with Porosity, Composites Part A: Applied Science and Manufacturing, 112: 100-110. - https://doi.org/10.1016/j.compositesa.2018.05.020
- Al Takash, A., Beringhier, M., Hammoud, M., Grandidier, J.C. (2018) Numerical approach based on the collection of the most significant modes to solve cyclic transient thermal problems involving different time scales, Journal of Computational Physics, 375 :950-959. - https://doi.org/10.1016/j.jcp.2018.08.059
- Beringhier, M., Djato, A., Maida, D., Gigliotti, M. (2018) A Novel Protocol for Rapid Identification of Anisotropic Diffusion Properties of Polymer Matrix Composite Materials with Complex Texture, Composite Structures, 201: 1088-1096. - https://doi.org/10.1016/j.compstruct.2018.05.142
- Foti, F., Gigliotti, M., Pannier, Y., Mellier, D., Lafarie-Frenot, M.C. (2018) The Effect of the Environment on High Temperature Fatigue of Cross-Ply C/Epoxy Laminated Composites, Composite Structures, 202: 924-934. - https://doi.org/10.1016/j.compstruct.2018.04.065

- Simar, A., Gigliotti, M., Grandidier, J.C., Ammar-Khodja, I. (2018) Decoupling of Water and Oxygen Diffusion Phenomena in order to Prove the Occurrence of Thermo-oxidation during Hygrothermal Aging of Thermosetting Resins for RTM Composite Applications, Journal of Materials Science, 53:11855–11872. - ISSN 0022-2461, doi: 10.1007/s10853-018-2350-0
- Sinchuk, Y., Pannier, Y., Gueguen, M., Gigliotti, M. (2017) Image-based Modeling of Moisture Swelling in 2D Textile Composites using a Global-Local Approach, Proc IMechE Part C: Journal of Mechanical Engineering Science – Special Issue: "Lightweight Design in Transportation Engineering" Guest Editors: Serge Abrate, Southern Illinois University, USA, Vincenzo Crupi, University of Messina, Italy, Gabriella Epasto, University of Messina, Italy, 232: 1505–1519. - ISSN: 0954-4062, doi: 10.1177/0954406217736789
- Sinchuk, Y., Pannier, Y., Gueguen, M., Tandiang, D., Gigliotti, M. (2017) Computed-Tomography based Modelling and Simulation of the Moisture Diffusion and Swelling of Textile Composite Materials, International Journal of Solids and Structures, 154: 88-96. - ISSN: 0020-7683, doi: 10.1016/j.ijsolstr.2017.05.045
- Simar, A., Gigliotti, M., Grandidier, J.C., Ammar-Khodja, I. (2017) Water Diffusion in RTM Textile Composites for Aircraft Applications, Advances in Aircraft & Spacecraft Science, 4: 573-583. - ISSN: 2287-528X, doi: 10.12989/aas.2017.4.5.573
- Gigliotti, M., Minervino, M., Lafarie-Frenot, M.C. (2016) Assessment of Thermo-oxidative Induced Chemical Strain by Inverse Analysis of Shrinkage Profiles in Unidirectional Composites, Composite Structures, 157: 320-336. - ISSN: 0263-8223, doi: 10.1016/j.compstruct.2016.07.037
- Gigliotti, M., Minervino, M., Lafarie-Frenot, M.C., Grandidier, J.C. (2016) Effect of Thermo-oxidation on the Local Mechanical Behaviour of Epoxy Polymer Materials for High Temperature Applications, Mechanics of Materials, 101: 118-135. - ISSN: 0167-6636, doi: 10.1016/j.mechmat.2016.07.003
- Pecora, M., Pannier, Y., Lafarie-Frenot, M.C., Gigliotti, M., Guigon, C. (2016) Effect of Thermo-oxidation on the Failure Properties of an Epoxy Resin, Polymer Testing, 52: 209-217. - ISSN: 0142-9418, doi: 10.1016/j.polymertesting.2016.04.008
- Gigliotti, M., Minervino, M., Lafarie-Frenot, M.C. (2016) Thermo-oxidative induced Shrinkage in Organic Matrix Composites for High Temperature Applications: Effect of Fibre Arrangement and Oxygen Pressure, Composite Structures, 146: 176-186. - ISSN: 0263-8223, doi: 10.1016/j.compstruct.2016.03.007
- Gigliotti, M. (2016) Residual Thermal Strains and Stresses in Organic Composite Materials, Journal of Thermal Stresses, 39: 667-703. - ISSN: 0149-5739, doi: 10.1080/01495739.2016.1169130
- Cinquin, J., Colin, X., Fayolle, B., Mille, M., Terekhina, S., Chocinski, L., Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C., Minervino, M., Cluzel, C., Daghia, F., Ladeveze, P., Zhang, F. (2016) Thermo-oxidation Behaviour of Organic Matrix Composite Materials at High Temperatures, Advances in Aircraft & Spacecraft Science, 3: 171-195. - ISSN: 2287-528X, doi: 10.12989/aas.2016.3.2.171
- Beringhier, M., Simar, A., Gigliotti, M., Grandidier, J.C., Ammar-Khodja, I. (2016) Identification of the Orthotropic Diffusion Properties of RTM Textile Composites for Aircraft Applications, Composite Structures, 137: 33-43. - ISSN: 0263-8223, doi: 10.1016/j.compstruct.2015.10.039
- Lin, Y., Gigliotti, M., Lafarie-Frenot, M.C., Bai, J., Marchand, M., Mellier, D. (2015) Experimental Study to Assess the Effect of Carbon Nanotube Addition on the Through-Thickness Electrical Conductivity of CFRP Laminates for Aircraft Applications, Composites Part B: Engineering, 76: 31-37. - ISSN: 1359-8368, doi: 10.1016/j.compositesb.2015.02.015
- Lin, Y., Gigliotti, M., Lafarie-Frenot, M.C., Bai, J. (2015) Effect of Carbon Nanotubes on the Thermoelectric Properties of CFRP Laminate for Aircraft Applications, Journal of Reinforced Plastics and Composites, 34: 173-184. - ISSN: 0731-6844, doi: 10.1177/0731684414565940
- Gigliotti, M., Lafarie-Frenot, M.C., Lin, Y., Pugliese, A. (2015) Electro-Mechanical Fatigue of CFRP Laminates for Aircraft Applications, Composite Structures, 127: 436-449. - ISSN: 0263-8223, doi: 10.1016/j.compstruct.2015.01.023
- Beringhier, M., Gigliotti, M. (2015) A Novel Methodology for the Rapid Identification of the Water Diffusion Coefficients of Composite Materials, Composites Part A: Applied Science and Manufacturing, 68: 212-218. - ISSN: 1359-835X
- Grandidier, J.C., Olivier, L., Lafarie-Frenot, M.C., Gigliotti, M. (2015) "Modeling the Pressure Dependent Solubility in a Thermoset Resin for Simulating Pressure Accelerated Thermo-oxidation Tests", Mechanics of Materials, 84: 44-54
- Minervino, M., Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2014) "A Coupled Experimental/Numerical Approach for the Modelling of the Local Mechanical Behaviour of Epoxy Polymer Materials", Journal of the Mechanics and Physics of Solids, 67: 129-151

- Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2014) “Vieillissement des Composites à Matrice Organique. Cas d’études”, in Techniques de l’Ingénieur, AM 5 322, Editions T.I., Paris, 34p
- Gigliotti, M., Minervino, M. (2014) “The Deformed Shape of Isotropic and Orthotropic Plates Subjected to Bending Moments Distributed along the Edges”, Meccanica, 49, p. 1367-1384
- Minervino, M., Gigliotti, M., Lafarie-Frenot, M.C., Grandidier, J.C. (2013), “The Effect of Thermo-oxidation on the Mechanical Behaviour of Polymer Epoxy Materials”, Polymer Testing, 32: 1020-1028
- Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2013) “Vieillissement des Composites à Matrice Organique. Outils de Modélisation”, in Techniques de l’Ingénieur, AM 5 322, Editions T.I., Paris, 17p
- Vu, D.Q., Gigliotti, M., Lafarie-Frenot, M.C. (2013) “The Effect of Thermo-Oxidation on Matrix Cracking of Cross-Ply [0/90]s Composite Laminates”, Composites Part A: Applied Science and Manufacturing, 44: 114-121
- Gigliotti, M., Pannier, Y., Minervino, M., Lafarie-Frenot, M.C., Corigliano, P. (2013) “The Effect of a Thermo-oxidative Environment on the Behaviour of Multistable [0/90] Unsymmetric Composite Plates”, Composite Structures, 106: 863-872
- Vu, D. Q., Gigliotti, M., Lafarie-Frenot, M.C. (2012) “Experimental Characterization of Thermo-oxidation-induced Shrinkage and Damage in Polymer-Matrix Composites” Composites Part A: Applied Science and Manufacturing, 43: 577-586
- Gigliotti, M., Minervino, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2012) “Predicting Loss of Bifurcation Behaviour of 0/90 Unsymmetric Composite Plates Subjected to Environmental Loads” Composite Structures, 94: 2793-2808
- Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2011) “Effects of Thermo-Oxidation on Composite Materials and Structures at High Temperatures” in Composite Materials in Engineering Structures, Editor: J.M. Davis, Materials Science and Technology Series, Nova Science Publisher, New York, ISBN : 978-1-61728-857-9. 52p. Référencé dans SCOPUS à partir de 2013
- Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2011) “Assessment of Chemo-Mechanical Couplings in Polymer Matrix Materials Exposed to Thermo-Oxidative Environments at High Temperatures and Under Tensile Loadings” Mechanics of Materials, 43: 431-443
- Gigliotti, M., Olivier, L., Vu D.Q., Grandidier, J.C., Lafarie-Frenot, M.C. (2011) “Local Shrinkage and Stress Induced by Thermo-Oxidation in Composite Materials at High Temperatures” Journal of the Mechanics and Physics of Solids, 59: 696-712
- Gigliotti, M., Grandidier, J.C., Lafarie-Frenot, M.C. (2011) “The Employment of 0/90 Unsymmetric Samples for the Characterisation of the Thermo-oxidation Behaviour of Composite Materials at High Temperatures” Composite Structures, 93: 2109-2119
- Gigliotti, M., Grandidier, J.C. (2010) “Chemo-Mechanics Couplings in Polymer Matrix Materials Exposed to Thermo-Oxidative Environments” Comptes Rendus Mécanique, 338: 164-175
- Lafarie-Frenot, M.C., Grandidier, J.C., Gigliotti, M., Olivier, L., Colin, X., Verdu, J., Cinquin, J. (2010) “Thermo-oxidation Behaviour of Composite Materials at High Temperatures: Review of Research Activities Carried Out within the COMEDI Program” Polymer Degradation and Stability, 95: 965-974
- Olivier, L., Baudet, C., Bertheau, D., Grandidier, J.C., Lafarie-Frenot, M.C. (2009) “Development of Experimental, Theoretical and Numerical Tools for Studying Thermo-oxidation of CFRP Composites” Composites Part A: Applied Science and Manufacturing, 40: 1008–1016
- Chocinski-Arnault L, Olivier L, Lafarie-Frenot MC. (2009) “Effects of thermal oxidation on an epoxy-amine thermoset studied by mechanical spectroscopy”. Materials Science and Engineering: A.; 521-522: 287-90.
- Rasoldier N, Colin X, Verdu J, Bocquet M, Olivier L, Chocinski-Arnault L, et al. (2008) “Model systems for thermo-oxidised epoxy composite matrices”. Composites Part A: Applied Science and Manufacturing, 39: 1522-9.
- Olivier, L., Ho, N.Q., Grandidier, J.C., Lafarie-Frenot, M.C. (2008) “Characterization by Ultra-micro Indentation of an Oxidized Epoxy Polymer: Correlation with the Predictions of a Kinetic Model of Oxidation” Polymer Degradation and Stability, 93: 489–497
- Lafarie-Frenot MC, Ho NQ. (2006) “Influence of free edge intralaminar stresses on damage process in CFRP laminates under thermal cycling conditions”. Composites Science and Technology; 66: 1354-65.
- Lafarie-Frenot MC, Rouquie S, Ho NQ, Bellenger V. (2006) “Comparison of damage development in C/epoxy laminates during isothermal ageing or thermal cycling”. Composites Part A: Applied Science and Manufacturing ; 37: 662-71.
- Rouquie S, Lafarie-Frenot MC, Cinquin J, Colombaro AM. (2005) “Thermal cycling of carbon/epoxy laminates in neutral and oxidative environments”. Composites Science and Technology; 65: 403-9.

- Lafarie-Frenot MC, Rouquie S. (2004) “Influence of oxidative environments on damage in c/epoxy laminates subjected to thermal cycling”. Composites Science and Technology; 64: 1725-35.