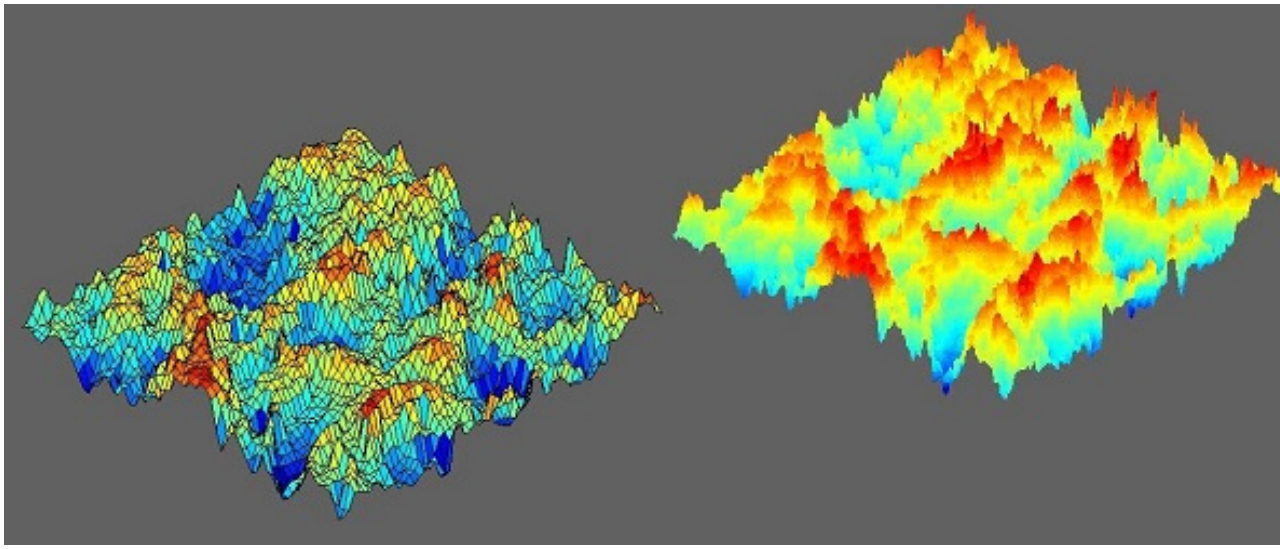
IMT INSTITUTE FOR ADVANCED STUDIES LUCCA

Research unit MUSAM
Multi-scale Analysis of Materials

Annual Report – 2014



Contents

Preface

This report provides an overview of the activities carried out by the research unit MUSAM (Multi-scale Analysis of Materials) in 2014, along with a summary of the main results achieved and an outlook on future directions of research.

MUSAM has been founded in November 2013 within the area of Computer Science and Applications of the IMT Institute for Advanced Studies Lucca to contribute to the research on complex technological systems by promoting the highest as possible scientific excellence in mathematical modelling, numerical analysis and experimental methods.

The research activities have been partially supported by the ERC Starting Grant CA2PVM *Multi-field and multi-scale Computational Approach to design and durability of Photovoltaic Modules* by the European Research Council which has made possible to finance three post-doctoral scholarships and to realize the MUSAM-Lab devoted to multi-scale characterization of materials and surfaces, the first experimental laboratory of the Institute. Additional resources have been provided by the Italian Ministry of Education, University and Research to the FIRB Future in Research Project *Structural Mechanics Models for Renewable Energy Applications*, supporting the activities of collaborators enrolled at Politecnico di Torino. Last but not least, the institutional support to one Assistant Professorship and four PhD scholarships is gratefully acknowledged.

Although much has to be done to increase the contribution and impact of the research unit within the interdisciplinary context of IMT, the scientific results achieved during 2014 are remarkable, with publications in top journals of mechanics (Computational Mechanics, Mechanics of Materials), energy (International Journal of Photoenergy, Energy Procedia) physics (Journal of Physics), as well as in multidisciplinary journals (Scientific Reports).

Noteworthy is the ability of the unit to attract PhD students and research scholars with international experience. The 160 Worldwide applications received for the PhD in Computational Mechanics characterized by an interdisciplinary educational programme are very promising for future joint initiatives in the area of Computer Science and Systems Engineering.

Finally, I would like to express my personal gratitude to Professor Alberto Bemporad, Director of the Institute, to the Colleagues for constructive discussions, and to all the collaborators and visiting scholars that have contributed with their passion and commitment to the scientific results achieved in 2014.

With sincere greetings from the beautiful City of Lucca,

Prof. Dr. Ing. Marco Paggi, 31.12.2014
(Director of the research unit)

1 Mission of the research unit

MUSAM –Multi-scale Analysis of Materials– is a research unit of the IMT Institute for Advanced Studies Lucca belonging to the area of *Computer Science and Applications*. The research unit contributes to the research and educational programmes of the Institute by developing mathematical models, computational methods and experimental techniques for the characterization and prediction of nonlinear phenomena in physical systems characterized by multiple scales or in the presence of multiple fields.

The web-site of the research unit is:
`http://musam.imtlucca.it`

The web-site of the MUSAM-Lab is:
`http://www.imtlucca.it/research/laboratories/musam-lab`

View of the MUSAM-Lab

2 Organization

The research unit is composed of:

- Prof. Dr. Ing. Marco Paggi (Director) `www.imtlucca.it/marco.paggi`
- Dr. Claudia Borri, Post-doctoral fellow responsible for the activities in the MUSAM-Lab
- Mr. Pietro Lenarda, PhD student of the cycle XXIX

Visiting scholars from other institutions involved in the activities of the research unit:

- Dr. Ing. Mauro Corrado, Assistant Professor, Visiting Professor at IMT Lucca and affiliated to Politecnico di Torino (Torino, Italy), currently Marie Curie Fellow at the École Polytechnique Fédérale de Lausanne (Lausanne, Switzerland)
- Dr. Ing. José Reinoso, Assistant Professor, Visiting Professor at IMT Lucca and affiliated to the Leibniz University of Hannover (Hannover, Germany) and to the University of Seville (Seville, Spain)

- Ing. Irene Berardone, PhD student of the cycle XXVIII at Politecnico di Torino and Visiting Scholar at the Institute for Solar Energy Research (Hamelin, Germany) from May 2014 to March 2015
- Ing. Andrea Infuso, PhD student of the cycle XXVIII at Politecnico di Torino and Visiting Scholar at the Université Paris-Est (Marne-la-Vallée, France) from May 2014 to November 2014
- Ing. Saheed Olalekan Ojo, PhD student of the cycle XXVIII at Politecnico di Torino
- Dr. Alberto Sapora, post-doctoral fellow at Politecnico di Torino till June 2014 and currently tenure-track Assistant Professor in the same university

3 Research activities

Research activities undertaken in 2014 covered fundamental topics of mechanics of materials and structures, such as thermo-elastic stress analysis, fracture, fatigue, and contact mechanics. Besides those topics, the unit promotes research in the field of computational materials science by combining computational methods proper of mechanics with advanced experimental techniques typical of materials science. This aim is pursued thanks to the experimental facilities of the MUSAM-Lab realized with the financial support of the European Research Council provided to the ERC Starting Grant CA2PVM (GA no. 306622). In line with the ERC StG mission, fundamental research is carried out in the field of photovoltaics in order to understand the phenomenon of cracking in solar cells, design new solutions to limit its effect, and increase the overall durability and reliability of this renewable energy technology.

4 Educational activities

The research unit contributes since November 2014 to a PhD curriculum on *Computational Mechanics* whose peculiarity stems from the strong interdisciplinarity of the educational programme. Courses on *Theory and Numerics for Ordinary and Partial Differential Equations* and on *Foundations of Probability Theory and Statistical Inference* provide the PhD students with a preliminary mathematical background. Computer skills are provided by the courses offered by the research unit SYSMA (*Principles of Concurrent and Distributed Programming*) and classes on optimization methods are offered by the research unit DYSCO (*Convex Optimization*). Depending on the specialization of the PhD students, courses on Image Analysis (*Machine Learning and Pattern Recognition*) and Networks theory (*Introduction to Networks Theory*) offered by PRIAn and Networks research units, respectively, can be selected. An advanced course on *Fracture and Contact Mechanics* introduces the students to the fundamentals

of these disciplines and presents possible advancements and innovative applications. Seminars on advanced topics of interest to the PhD students are also delivered by invited visiting scholars.

The originality of the PhD curriculum relies in the multidisciplinary educational programme focusing on mathematical and numerical methods, optimization and control theory and computer science, rather than being a traditional monodisciplinary programme. This is deemed to be essential today to make a breakthrough in the analysis and simulation of complex problems in science and technology, especially due to the advent of innovative materials with heterogeneous microstructures over multiple scales, metamaterials, morphing structures and hierarchical composites and surfaces. Indeed, advancements require multidisciplinary skills ranging from mathematical and material modelling to parallel and distributed programming, passing through optimization theory and computational methods to effettively address problems of high technological relevance with an innovative methodology.

In addition to the main contribution to the PhD Curriculum in *Computational Mechanics*, the course on *Theory and Numerics for Ordinary and Partial Differential Equations* and the long seminar on *Management of Intellectual Property and Fund Raising* are offered to all the PhD Tracks of the Institute. In particular, the course on *Theory and Numerics for Ordinary and Partial Differential Equations* provides the methods for the numerical treatment of linear ordinary and partial differential equations, the fundamentals of the Laplace transforms, numerical methods for differentiation and integration, interpolation methods, and the basic knowledge of the finite difference method and of the finite element method to understand and solve practical problems arising in heat conduction, quantitative finance and linear elasticity. The course is propedeutic to other intermediate and advanced courses in economics (*Quantitative Finance* and *Introduction to Stochastic Control – Theory and Applications*) and to the advanced course on *Fracture and Contact Mechanics* which deals with nonlinear problems.

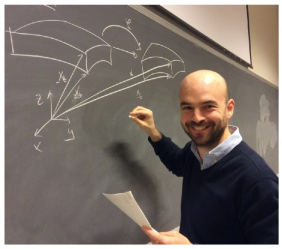
5 Guest scholars and seminars

During 2014, two scholarships have been funded within the ERC StG project to support the long stays by Dr. José Reinoso and Dr. Mauro Corrado as visiting professors. The research unit has also received short visits by Prof. Davide Bigoni, Dr. Andrea Bacigalupo and Dr. Lorenzo Morini from the University of Trento, Dr. Enzo Marino from the University of Florence, Prof. Vladislav Mantic from the University of Seville, Dr. Gianluca Fiori from the University of Pisa, Prof. Qi-Chang He from the Université Paris-EST, and Prof. Luigi Gambarotta and Prof. Roberta Massabó from the University of Genova.
A list of seminars organized by the research unit is provided below.

- Dr. M. Corrado, Politecnico di Torino, visiting professor from February 11 to March 11, 2014. Seminar: An XFEM strategy to analyse the scale-

slenderness-reinforcement failure mode transitions in RC beams (February 27, 2014).

- Prof. D. Bigoni, University of Trento, visiting scholar from March 16 to March 17, 2014 and from November 28 to November 30, 2014. Seminar: Configurational forces in elastic structures (March 17, 2014).
- Dr. J. Reinoso, Leibniz University of Hannover, visiting professor from March 1 to April 30, 2014 and visiting scholar from December 14 to December 21, 2014. Seminar: Advanced nonlinear three-dimensional finite element shell formulations for composite structures (March 20, 2014).
- Prof. V.V. Mantič, University of Sevilla, visiting scholar from July 12 to July 14, 2014. Seminar: FFM and related energetic approaches to the delamination and debond problems in composites (July 14, 2014).
- Dr. G. Fiori, University of Pisa. Seminar: Graphene-based solar cells (September 11, 2014)
- Dr. A. Bacigalupo, University of Trento. Seminar: Second-gradient homogenized model for wave propagation in heterogeneous periodic media (November 25, 2014).
- E. Marino, University of Florence. Seminar: A novel numerical strategy for the simulation of irregular nonlinear waves and their effects on the dynamic response of offshore wind turbines (November 25, 2014).
- L. Morini, University of Trento. Seminar: Remarks on the energy release rate for an antiplane moving crack in couple stress elasticity (November 25, 2014).

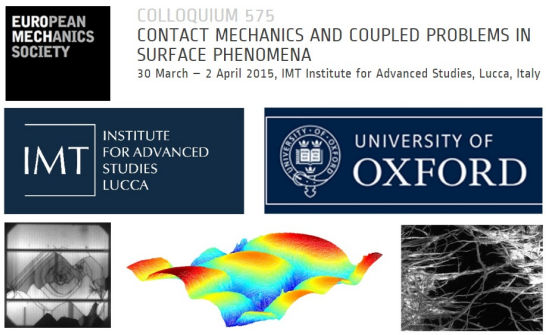


Some photos taken during research seminars

6 Outreach activities

The research unit participates to the activities of the IEA-PVPS (International Energy Agency – Photovoltaic Power Systems Programme) Committee of Task 13 on Performance and Reliability of Photovoltaic Systems in the period 2015-2017, see `http://www.iea-pvps.org`. The Task 13 aims at publishing reports on field data degradation of PV modules and on critical examination of crack detection methods, along with guidelines for improved financial plans accounting for maintenance costs. These reports are conceived to have impact on the photovoltaic industry sector and on policy makers.

In the field of contact mechanics, a joint proposal together with Prof. D.A. Hills of the University of Oxford for a conference has been approved in July 2014 by the European Mechanics Society and the research unit is going to organize the EUROMECH Colloquium 575 on Contact Mechanics and Coupled Problems in Surface Phenomena to be held in Lucca from March 30 to April 2, 2015, see `http://575.euromech.org`. Following the tradition of EUROMECH Colloquia, the event will be organized in one single session with oral presentations delivered by internationally recognized experts in the field.



The research unit has also organized several minisymposia and special sessions in international conferences, see below. Its members have delivered invited seminars and lectures at conferences and universities disseminating research results and promoting the visibility of the Institute in the field of mechanics.

6.1 Minisymposia organized in international conferences

- Minisymposium Fracture and Contact Mechanics for Interface Mechanical Problems, 11th World Congress on Computational Mechanics, 2014, Barcelona, Spain (Organized by M. Paggi, A. Carpinteri, P. Wriggers).
- Special session Numerical and Experimental Research on the Durability of Photovoltaic Modules, 1st International Symposium on Energy Challenges and Mechanics, 2014, Aberdeen, Scotland (Organized by J. Reinoso, M. Paggi, F. Haase).

- Special session Material Simulation for Energy Applications, 1st International Symposium on Energy Challenges and Mechanics, 2014, Aberdeen, Scotland (Organized by D. Antoun, L. De Lorenzis, M. Paggi, A. Piccolroaz).

6.2 Invited seminars and lectures

- Modelling and simulation of fracture in classical and hierarchical polycrystalline materials towards the design of super-resistant cutting tools, invited lecture by M. Paggi at the Special Interest Seminar on Simulation and Modelling in Hard Materials, Euro PM2014 Congress & Exhibition, Salzburg, Austria, 21-24/09/2014.

- Flaw tolerance of continuum and discrete mechanical systems: The roles of heterogeneity and nonlocality (M. Paggi, A. Infuso), opening lecture by M. Paggi at the ECT* Workshop on New Frontiers in Multiscale Modelling of Advanced Materials, Trento, Italy, 17-20/06/2014.

- Nonlinear fracture dynamics of laminates with finite thickness adhesives, seminar by M. Paggi at the University of Seville, Seville, Spain, 27/6/2014.

- Multi-physics modelling of cracking in quasi-brittle materials for energy applications, seminar by M. Paggi at the University of Trento, Trento, Italy, 18/6/2014.

- Experimental evidence of electro-thermo-elastic coupling in quasi-brittle materials for energy applications, seminar by M. Paggi at the University of Trento, Trento, Italy, 18/6/2014.

- Quantitative analysis of cracking in photovoltaic modules using a multi-physics approach, seminar by M. Paggi at the Institute of Solar Energy Research, Hamelin, Germany, 3/6/2014.

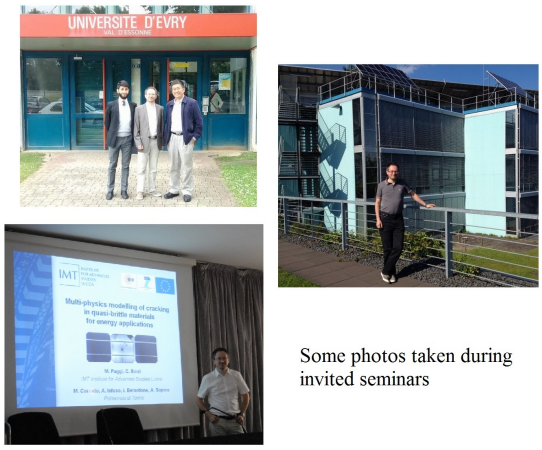
- An overview on contact and fracture mechanics for interface problems, seminar delivered by M. Paggi at the University of Evry, Evry, France, 23/05/2014.

- Multi-scale and multi-physics models applied to interface problems, seminar by M. Paggi at the Université Paris-EST, Marne-La-Vallée, France, 16/5/2014.

- Fracture dynamics of laminates with finite thickness interfaces, seminar by M. Paggi at the Université Paris-EST, Marne-La-Vallée, France, 29/04/2014.

- Mechanical challenges in the durability of photovoltaic modules, seminar by M. Paggi at the Institute for Mechanics of the Technical University of Berlin, Berlin, Germany, 17/12/2013.

- Modelling of cracking in PV modules: Physical aspects and Computational Methods, opening lecture by M. Paggi at the Workshop on Measurements and Models for PV-Module analysis, Institute of Solar Energy Research, Hamelin, Germany, 5/11/2013.

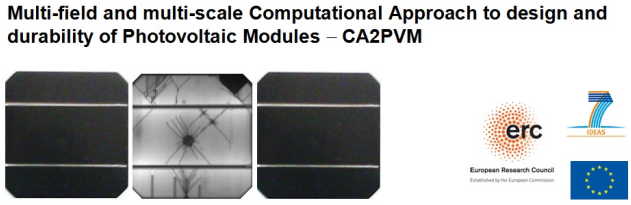


Some photos taken during invited seminars

7 Funding and technology transfer

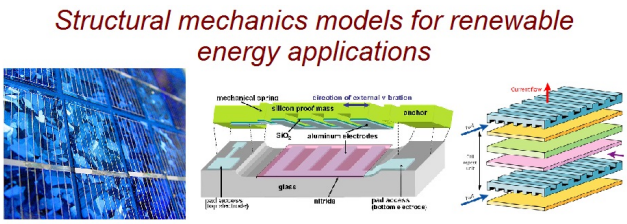
7.1 Funding

Two projects, one supported by the European Research Council and another by the Italian Ministry of Education, University and Research are currently ongoing. The ERC Starting Grant CA2PVM on Multi-scale and Multi-Physics Computational Methods for the Design and Durability of a Photovoltaic Modules will end in December 2017 and a list of scientific results is continuously updated on the project web-site `http://musam.imtlucca.it/CA2PVM.html`.



The FIRB Future in Research Project on Structural Mechanics Models for Renewable Energy Applications involving Politecnico di Torino, the University

of Salento and the University of Trento as partners is currently at its third year and will end in March 2016, see `http://musam.imtlucca.it/FIRB.html`.



Although not funded, the research unit has been invited to participate as an international expert to a research proposal on renewable energy coordinated by the University of Columbia for the US National Science Foundation, together with the Northwestern University, Virginia Tech and the Hong Kong University of Science and Technology. As a further evidence of its visibility, the research unit has been invited at the end of 2014 by a US industry of the photovoltaic sector to contribute as a partner to a project proposal on quality assessment of photovoltaics for a call of the US Department of Energy, together with the US National Renewable Energy Laboratory and the Institute of Solar Energy Research, Hamelin, Germany.

7.2 Technology transfer

The research unit has carried out joint research activities with Solbian Energie Rinnovabili and Applied Materials Inc., both companies active in the field of photovoltaics that provided endorsement to the ERC StG CA2PVM.

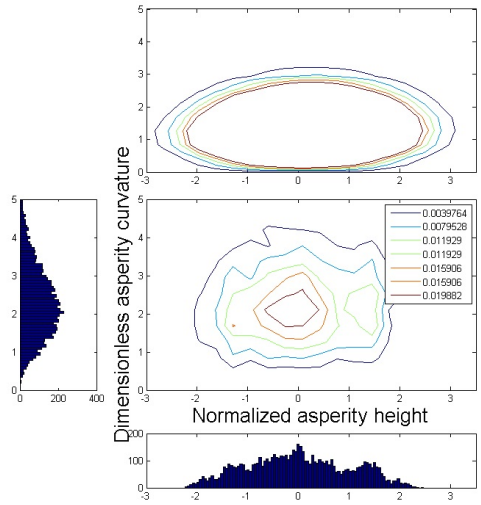
Activities aiming at fostering technology transfer to the local industries in the sectors of paper tissue, naval engineering, and photovoltaics have also been carried out during 2014. MUSAM has partecipated to a seminar organized by Unione Industriali di Lucca to promote joint PhD projects and Prof. Paggi has delivered a lecture to representatives of local industries organized by Lucense SCpA in the framework of the Innopaper initiatives. Technology transfer is therefore expected to be intensified during 2015.

8 Scientific results

The members of the research unit have co-authored 19 articles accepted in peer-reviewed international journals. Other 5 articles are currently under peer-review. Prof. Paggi published as senior author in the majority of the papers. Articles co-authored by PhD students are 7 over 19 (9 over 24 considering also the submitted manuscripts under review). Articles A.4, A.11, A.15 and A.18 are the outcome of international collaborations, as well as the articles A.21 and A.22 under review. Article A.20 under review is the result of a joint research involving the units DYSCO and MUSAM.

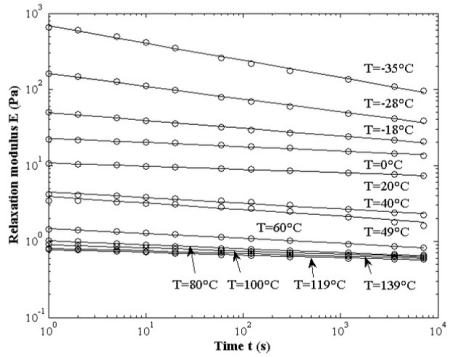
The key results are summarized in the following items:

- Development of a numerical tool for the multi-resolution statistical and spectral characterization of textured surfaces such as antireflective coatings and hydrophobic surfaces sampled by a confocal profilometer [A.1].



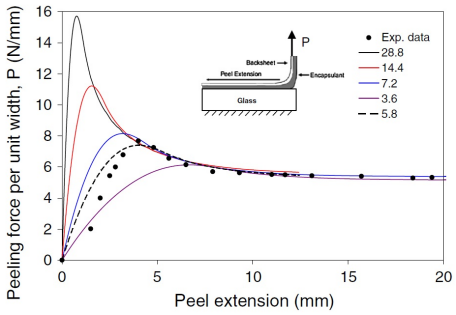
Comparison between experimental and theoretical joint probability density functions

- Thermo-visco-elastic constitutive model for epoxy vinil acetate based on fractional calculus and comparison with experiments [A.2].



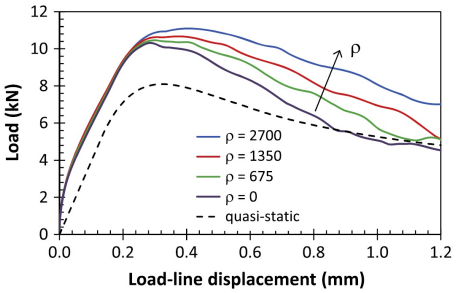
Relaxation modulus of epoxy vinil acetate: model and experiments

- Application of model order reduction techniques to modelling heat conduction in photovoltaic laminates [A.3].
- Development of a novel consistent interface element formulation for large displacements decohesion and application to peeling [A.5].



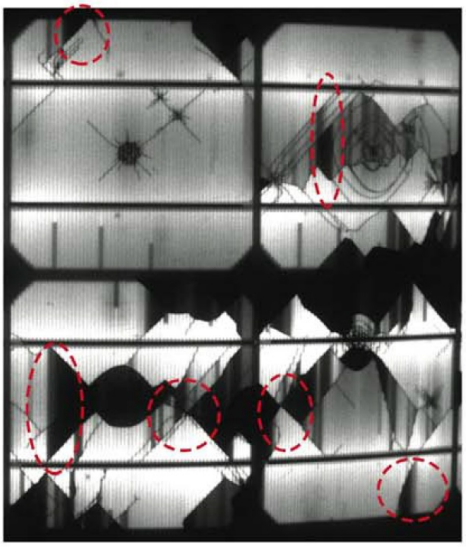
Simulation of a peeling test: model and experiments

- Development of a novel interface finite element for the dynamic simulation of adhesives with finite thickness. The method allowed to investigate the interplay between dynamics and nonlinear fracture mechanics using a fully implicit solution scheme [A.4 and A.12].



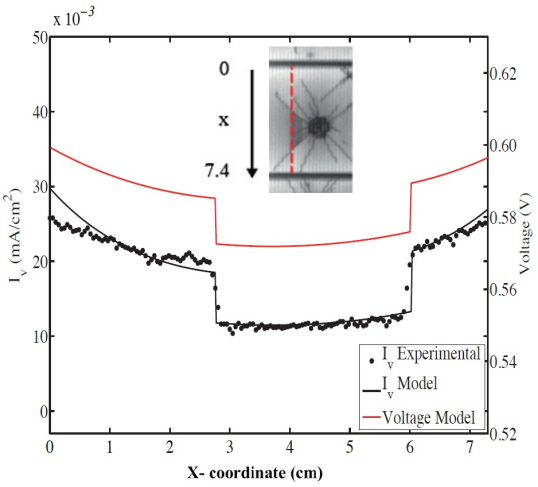
Double cantilever beam test: the effect of the adhesive mass density

- Innovative experimental testing showing the interplay between mechanical deformation and the electric response of cracked solar cells embedded in photovoltaic modules [A.6 and A.10].



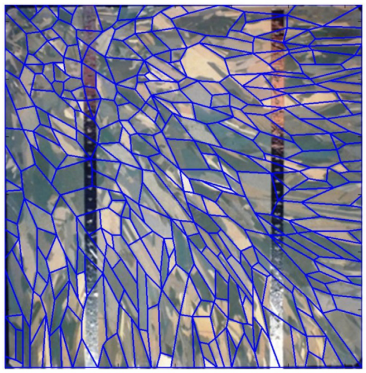
Electric inactive areas in cracked solar cells during bending

- Development of an electric model for mono- and poly-crystalline solar cells in the presence of cracks [A.7].



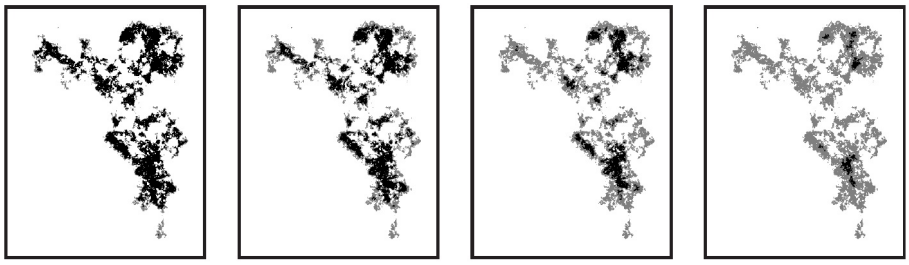
Vertical current in cracked solar cells: model and experiments

- Image analysis applied to grain boundary detection in polycrystalline solar cells and numerical study of intergranular and transgranular cracking [A.13].



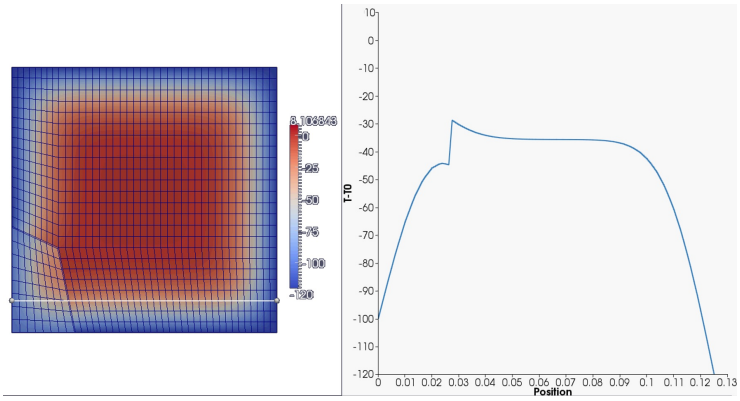
Grain boundary detection in polycrystalline solar cells

- Universal scaling laws in the tangential contact between rough surfaces under partial slip [A.11].



Transition from full stick to full slip (from left to right) in case of a rough surface. Black contact areas are domains in full stick condition, whereas grey contact areas represent slipped domains.

- Advancements in the understanding of the scaling laws governing fatigue of rough cracks [A.14 and A.15].
- Developement of a thermo-elastic cohesive zone model for the simulation of transient heat conduction at partially bonded interfaces [A.17].



Temperature distribution inside a cracked solar cells

8.1 Peer-reviewed journal publications

A.1 Borri, C and Paggi, M. Topological characterization of antireflective and hydrophobic rough surfaces: are random process theory and fractal modeling applicable? Journal of Physics D: Applied Physics, 48 (4) paper no. 045301 `http://dx.doi.org/10.1088/0022-3727/48/4/045301`

A.2 Paggi, M and Sapora, A. An accurate thermo-visco-elastic rheological model for ethylene vinyl acetate based on fractional calculus. International Journal of Photoenergy, in press.

A.3 Ojo, SO and Grivet Talocia, S and Paggi, M. Model order reduction applied to heat conduction in photovoltaic modules. Composite Structures, 119. pp. 477-486 (2015) http://dx.doi.org/10.1016/j.compstruct.2014.09.008

A.4 Corrado, M and Paggi, M. Nonlinear fracture dynamics of laminates with finite thickness adhesives, Mechanics of Materials, 80 part B. pp. 183-192 (2015) http://dx.doi.org/10.1016/j.mechmat.2014.07.012

A.5 Reinoso, J and Paggi, M. A consistent interface element formulation for geometrical and material nonlinearities, Computational Mechanics, 54. pp. 1569-1581 (2014) http://dx.doi.org/10.1007/s00466-014-1077-2

A.6 Paggi, M and Berardone, I and Infuso, A and Corrado, M. Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules. Scientific Reports, 4. pp. 1-7 (2014) http://dx.doi.org/10.1038/srep04506

A.7 Berardone, I and Corrado, M and Paggi, M. A generalized electric model for mono and polycrystalline silicon in the presence of cracks and random defects. Energy Procedia, 55. pp. 22-29 (2014) http://dx.doi.org/10.1016/j.egypro.2014.08.005

A.8 Infuso, A and Paggi, M. Flaw-tolerance of non local discrete systems and interpretation according to network theory. Fracture and Structural Integrity, 29. pp. 302-312 (2014) http://dx.doi.org/10.3221/IGF-ESIS.29.26

A.9 Corrado, M and Paggi, M and Carpinteri, A. A multi-scale numerical method for the study of size-scale effects in ductile fracture. Metals, 4 (3). pp. 428-444 (2014) http://dx,doi.org/10.3390/met4030428

A.10 Paggi, M and Berardone, I and Infuso, A and Corrado, M. Electrical recovery and fatigue degradation phenomena in cracked silicon cells. Journal of Energy Challenges and Mechanics, 1 (1). pp. 1-5 (2014) http://www.nscj.co.uk/JECM/PDF/1-1-4-Marco%20Paggi.pdf

A.11 Paggi, M and Pohrt, R and Popov, V. Partial-slip frictional response of rough surfaces. Scientific Reports, 4 art. no. 5178 (2014) http://dx.doi.org/10.1038/srep05178

A.12 Corrado, M and Paggi, M. Dynamic nonlinear crack growth at interfaces in multi-layered materials. Procedia Materials Science, 3. pp. 1971-1976. (2014) http://dx.doi.org/10.1016/j.mspro.2014.06.317

A.13 Infuso, A and Corrado, M and Paggi, M. Image analysis of polycrystalline solar cells and modeling of intergranular and transgranular cracking. Journal of the European Ceramic Society, 34 (11). pp. 2713-2722 (2014) http://dx.doi.org/10.1016/j.jeurceramsoc.2013.12.051 http://arxiv.org/abs/1410.0256

A.14 Carpinteri, A and Paggi, M. The effect of crack size and specimen size on the relation between the Paris and Wöhler curves. Meccanica, 49 (4). pp. 765-773 (2014) http://dx.doi.org/10.1007/s11012-014-9908-y

A.15 Paggi, M and Plekhov, O. On the dependency of the parameters of fatigue crack growth from the fractal dimension of rough crack profiles. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 228 (12). pp. 2059-2067 (2014) http://dx.doi.org/10.1177/0954406213515643 http://arxiv.org/abs/1410.0266

A.16 Carpinteri, A and Paggi, M. Lagrange and his Mécanique Analytique: from Kantian noumenon to present applications. Meccanica, 49 (1). pp. 1-11 (2014) http://dx.doi.org/10.1007/s11012-013-9864-y

A.17 Sapora, A and Paggi, M. A coupled cohesive zone model for transient analysis of thermoelastic interface debonding. Computational Mechanics, 53. pp. 845-857 (2014) http://dx.doi.org/10.1007/s00466-013-0934-8 http://arxiv.org/abs/1410.0242

A.18 Garcia, IG and Paggi, M and Mantič, V. Fiber-size effects on the onset of fiber–matrix debonding under transverse tension: comparison between cohesive zone and finite fracture mechanics models. Engineering Fracture Mechanics, 115. pp. 96-110 (2014) http://dx.doi.org/10.1016/j.engfracmech.2013.10.014

A.19 Sapora, A and Codegone, M and Barbero, G and Evangelista, LR. Adsorption and desorption phenomena and diffusion of neutral particles in the hyperbolic regime. Journal of Physics A: Mathematical and Theoretical, 47, 015002 (2014) http://dx.doi.org/10.1088/1751-8113/47/1/015002

8.2 Articles submitted and under review

A.20 Bemporad, A and Paggi, M. Optimization algorithms for the solution of the frictionless normal contact between rough surfaces.

A.21 Paggi, M and Reinoso, J. An anisotropic large displacement cohesive zone model for fibrillar or crazing interfaces.

A.22 Paggi, M and He, Q-C. Evolution of the free volume between rough surfaces in contact.

A.23 Spertino, F and Ciocia, A and Di Leo, P and Tommasini, R and Berardone I and Corrado, A and Infuso, A and Paggi, M. A monitoring and diagnosis procedure in grid-connected photovoltaic systems to quantify the sources of losses.

A.24 Infuso, A and Paggi, M. Computational modelling of discrete mechanical systems and complex networks: Where we are and where we are going. Frontiers in Materials, invited opinion article.

9 Future perspectives

The target of the research unit is to promote fundamental research in mechanics and the integration between materials science and computational methods. In the Institute context, the natural role of the unit is to provide quantitative methods, mathematical and numerical modelling and simulation for problems governed by partial differential equations, common to physics, engineering and economics. Therefore, if on the one hand the highest level of specialization in the fields of fracture and contact mechanics should be cultivated, on the other hand it is desirable to increase the multidisciplinarity of the applications. In this regard, on a much larger scale, successful examples of interdisciplinary centres to be taken as reference are those on computational mathematics and engineering like the Center for Advanced Modelling Science CADMOS in Switzerland on modelling of complex systems, and the interdisciplinary Centre on Computational Engineering CCE at MIT, developing new computational methods relevant to engineering disciplines. Regarding the integration of computational mechanics and materials science, a reference Institute is the Laboratorie de Modelisation et Simulation Multi-Echelle of the Université Paris-EST with whom MUSAM is collaborating. The Centre d'Enseignement et de Recherche en Mathématiques et Calcul Scientifique CERMICS at the École des Ponts ParisTech, with whom Prof. Paggi has made a preliminary contact, is also a reference centre promoting a large spectrum of applied mathematics, especially on modelling, numerical analysis and optimization, contributing to the project MATHRISK related to risk assessment in financial markets.

The research unit composition will increase of 6 persons in 2015: three PhD students (Ing. Valerio Carollo, Ing. Paolo Cinat, and Ing. Vigneswaran Govindarajan) already joined the unit in November 2014, two post-docs (Dr. Ing. Yogesh Sonavane and Dr. Ing. Pattabhi Ramaiah) will join the unit at the beginning of 2015 supported by scholarships provided by the ERC StG and one Assistant Professor (Dr. Ing. Andrea Bacigalupo) joined the unit at the end of 2014. Since all these contracts are 3 years long, it is possible to draw mid-term perspectives for the research unit.

In addition to the ongoing research on durability and multi-physics modelling of photovoltaics, new directions detailed below can be planned. They aim at strengthening and promoting the collaboration with the other research units of the Institute, also in view of the common interdisciplinary PhD programme in *Computer Science and Systems Engineering* activated from the cycle XXXI.

- Application of optimization algorithms to contact mechanics between rough surfaces; coupling of FEM with optimization algorithms for the design and control of smart interfaces.

- Formal description of innovative design criteria including structural mechanics, optimization and computer science methodologies for morphing structures and metamaterials as examples of complex cyber-physical systems.

- Numerical treatment of stochastic partial differential equations.
- Image analysis applied to polycrystalline material microstructures.
- Study of the analogies between mechanics of discrete systems and transport and socio-economical networks in order to explore the applicability and the limitations of simulation methods used in mechanics when applied to other disciplines.