

DER Génie Civil & Environnement of ENS Paris-Saclay

M2 « Materials, Structures & Energy for Sustainable Construction »

Head: Rachid BENNACER, Professor ENS Paris-Saclay, LMPS

Department **DER Génie Civil & Environnement**, École Normale Supérieure Paris-Saclay,

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proposes a research-oriented Master program in 2 years (year M1 followed by year M2), entitled

« Materials, Structures & Energy for Sustainable Construction »

and valued 120 credits (120 ECTS) in the European Credit Transfer and Accumulation System.

The first year of Master (M1, 60 ECTS) is taught in French. It comprises two semesters of courses, generally from early September to mid-January and from mid-January to mid-May. They are followed by an internship of at least two months.

The second year of Master (M2, 60 ECTS) is taught in English, with a few optional courses being taught in French. The year M2 is organized in 2 semesters, each valued 30 ECTS: semester S1, usually from early September to the end of February, and semester S2 from March to August, dedicated to a research internship. It comprises two main M2 programs:

- Program « *Modeling & Computing for Construction Engineering* »,
- Program « *Materials for Sustainable Construction & Environment* »,

The two main M2 programs differ in the mandatory courses followed in Semester S1 (30 ECTS, see lists provided next). They also differ in the research topics addressed in Semester S2 (30 ECTS), made up of

- a State-of-the-Art Report (STAR, 7 ECTS),
- a Research for All communication project (2 ECTS) or an Opening Course (“UE libre” for 2 to 3 ECTS) or an Autonomous Learning Instruction (3 ECTS),
- a Scientific Training Period in a research lab such as LMPS (own research project, 21 ECTS).

Note that refresher courses are offered to all students accepted into both M2 programs as a two-week class in September.

Semester S2 of the M2 programs

Semester S2 (from March to August) of both M2 programs is constituted of 30 ECTS, generally:

- **State-of-the-Art Report** (STAR, 7 ECTS),
Contact: F. Gatuingt, Professor ENS Paris-Saclay, LMPS.

Each student carries out individual bibliography research on a scientific subject under the guidance of a member of Laboratoire de Mécanique Paris-Saclay (LMPS), UMR CNRS 9026.

- **Research for All** (2 ECTS),
Contact: A. Fau, Assistant Professor ENS Paris-Saclay, LMPS.

This project aims to prepare students for communicating scientific results related to the STAR subject, such as writing an abstract, a list of highlights, and preparing a graphical abstract.

- **Scientific Training Period** (21 ECTS),

Contact: A. Fau & K. Abahri, Assistant & Associate Professors ENS Paris-Saclay.

The internship enables the student to gain research experience within a research group. A research project is carried out, including a bibliography and an own investigation (analytical development, modeling, or experiment). The Master program organizes a few collective and individual guidance sessions.

After agreement with the heads of the M2 programs, the opening course(s) can be chosen either among the Master programs lists of courses (see lists provided next), or can be chosen from another M2 or among those proposed by the Graduate School *Engineering and System Science*. Examples of Opening Courses are:

- Course “UE Sport” (2.5 ECTS)
- Autonomous-Learning course (3 ECTS)
- Course from other M2 programs.

Information for exchange students (Erasmus, other university partnerships)

If you plan to join the M2 program for one semester or one year as part of an exchange program (Erasmus or other partnership between your University or Engineering School and ENS Paris-Saclay), we strongly encourage you to contact us to draw up your learning agreement. Please contact both R. Bennacer (rachid.bennacer@ens-paris-saclay.fr) and R. Desmorat (rodrique.desmorat@ens-paris-saclay.fr), in charge of the Master national and international relationships, and put in copy

- A. Fau (amelie.fau@ens-paris-saclay.fr), if you plan to follow the « *Modeling & Computing for Construction Engineering* » Master 2 Program,
- K. Abahri (kamilia.abahri@ens-paris-saclay.fr), if you plan to follow the « *Materials for Sustainable Construction & Environment* » Master 2 Program.
- F. Gatuingt (fabrice.gatuingt@ens-paris-saclay.fr), if you plan to follow the « *Computational Methods for Construction Engineering* » Master 2 Program.

Professors of DER Génie Civil & Environnement of ENS Paris-Saclay

- **Farid Benboudjema** graduated from ENS Paris Saclay (former ENS Cachan) in 1999 and obtained a PhD in Civil Engineering from Université Paris-Est. He is currently Professor at ENS Paris-Saclay and head of “Mention Génie Civil” at Université Paris-Saclay. He leads a research chair on Assessing Concrete Foundations for Electricity Transmission, funded by Réseau de Transport d’Électricité (RTE) and the French National Research Agency. His research focuses on cementitious materials, with emphasis on early-age behavior, long-term durability, cracking, heat release, and mass transport. He develops experimental devices, multi-scale modelling approaches, and numerical simulation tools. He is the author of a book, several book chapters, and over 70 peer-reviewed articles. He has obtained more than 30 research grants from national agencies and industry.
- **Rachid Bennacer** is Professeur des Universités since 2008. His research at Laboratoire de Mécanique Paris-Saclay (LMPS) spans building materials for energy applications, durability, and renewable energy systems. He has occupied several key roles, including dean of the Civil/Environmental Department, director of research and entrepreneurship at ECAM-EPMI, and coordinator of International Affairs for PhD programs at Paris-Saclay University. Additionally, he served as Vice Dean of the ISS Graduate School. Currently, he is President of the ENS Paris-Saclay Special Executive Committee and Vice President for Research (Sciences & Engineering)

at Paris-Saclay University. He has published more than 300 research articles and co-authored several books/book chapters. His work mixes fundamental and industrial applications. He is included among the world's top 2% most influential scientists, as listed in the "World's Top 2% Scientists" ranking published by Stanford University.¹

- **Rodrigue Desmorat** is Professeur des Universités at ENS Paris Saclay (former ENS Cachan) since 2002. His research at Laboratoire de Mécanique Paris-Saclay (LMPS) spans Damage Mechanics — including ductile, creep, fatigue, quasi-brittle failures and nonlocal damage — and the fundamentals of Continuum Mechanics. He has published approximately 90 research articles and co-authored two books: Engineering Damage Mechanics (Springer, 2005, 2010) and Mécanique des Matériaux Solides (Dunod, 2009, 2021). His work bridges academic theory and industrial applications, supporting the design of safer, more durable engineering structures. He is included among the world's top 2% most influential scientists, as listed in the "World's Top 2% Scientists" ranking published by Stanford University.¹
- **Fabrice Gatuingt** is Professeur des Universités at ENS Paris Saclay (former ENS Cachan) since 2011 and currently Head of the Civil Engineering and Environment Research Department. He specialises in Civil Engineering, with a particular focus on the behaviour of concrete and structural materials under extreme loads. From January 2026, he will head the Research Federation for Ecological Transition and Sustainability in Construction, which aims to bring together and coordinate French scientific experts to radically transform practices in the construction sector, making them more sustainable, resilient and compatible with climate and environmental challenges.

¹ <https://ens-paris-saclay.fr/actualite/10-chercheurs-du-lmps-dans-le-classement-stanford-en-2024>

M2 Program Modeling & Computing for Construction Engineering

Contact: Amélie Fau, Assistant Professor ENS Paris-Saclay, LMPS.

The **Modeling & Computing for Construction Engineering** Master 2 program offers advanced training for future researchers, engineers, and designers in the mechanics of Civil Engineering materials and structures. Particular attention is paid to performance under extreme conditions that exceed standard regulatory requirements. Emphasis is placed on the design and analysis of structures subjected to complex loading, including dynamic, multi-physics, and stochastic (random) effects, as well as damage and failure of both materials and structures.

Students develop a solid foundation in scientific methodology, including bibliography analysis, experimental investigation, and the presentation of scientific results. The program develops multidisciplinary skills, combining state-of-the-art experimental tools (e.g., hybrid testing, Digital Image Correlation) **with theoretical and numerical modeling**. **Key points** are understanding and simulating non-linear, possibly softening, mechanical behavior of Civil Engineering materials and structures.

The academic team comprises senior researchers from the *Laboratoire de Mécanique Paris-Saclay* (LMPS, Unité Mixte de Recherche Université Paris-Saclay - CentraleSupélec - ENS Paris Saclay - CNRS). It is supplemented by international researchers, depending on the stays of visiting professors (Professeurs Invités) and visiting scientists. The academic program is complemented by visits to scientific facilities in the Paris-Saclay scientific environment (Synchrotron, CEA,...). Scientific conferences are also organized, either dedicated to the students of the **Modeling & Computing for Construction Engineering** M2 program and/or in collaboration with LMPS research groups, to familiarize students with local and international research activities related to the subjects covered by the M2 program.

Program Objectives:

- Bridge the gap between experiments (observations, mechanical responses) and structural modeling for supporting sustainable construction.
- Prepare students for research and engineering careers involving high-performance simulation and design under complex mechanical and environmental conditions.
- Offer **hands-on research experience** through a supervised Scientific Training Period in a research lab.
- Propose modern, research-based, and high-level courses.

Key Skills Acquired:

- Advanced experimental investigation for construction engineering (hybrid testing, Digital Image Correlation, etc.)
- Understanding and modeling deformation and degradation mechanisms in materials (durability, porous media, aging, etc.)
- Analysis of damage, rupture, and failure in Civil Engineering materials and structures
- Mechanics of structures under extreme and non-standard conditions
- Finite Element computation of non-linear structural responses.

Semester S1 (from September to January) of the **Modeling & Computing for Construction Engineering** M2 program is organized as follows.

Mandatory courses for a total of 6 ECTS

- Digital Image Correlation and Identification (part I) (1.5 ECTS), F. Hild
- Non-linear Finite Element method (3 ECTS), A. Fau
- Thermodynamics of solid materials (part I) (1.5 ECTS), R. Desmorat

Choice of courses for a total of 24 ECTS among the following

- Coupled energy and mass transfers in porous media (3 ECTS), R. Bennacer
- Control of active and reactive systems (part I) (1.5 ECTS), R. Bennacer
- Thermodynamics of solid materials (part II, porous media) (1.5 ECTS), R. Desmorat
- Digital Image Correlation and Identification (part II) (1.5 ECTS), F. Hild
- Structures subjected to transient loads (3 ECTS), F. Gatuingt
- Reduced and surrogate modeling for construction engineering (3 ECTS), A. Fau
- Continuum Damage Mechanics for quasi-brittle materials (3 ECTS), R. Desmorat
- Advanced structural modeling (3 ECTS), F. Gatuingt
- Advanced formulations of rational mechanics & its coupling (3 ECTS), R. Desmorat
- Scientific machine learning and applications to construction engineering (3 ECTS), D. Clouteau
- Delayed behavior of construction materials (3 ECTS), F. Benboudjema
- Opening Course

Each student also follows three 6-hour **Supplementary** courses, built as add-on to the 10 courses. **Supplementaries** are offered in groups of up to four students. The “Supplementary” offers time and a platform for scientific conversation between students and educational instructors. The form of the **Supplementary** may differ for each course. For instance, physical or virtual experiments, research papers, and theoretical developments are proposed.

The Learning Agreements are individually customized, offering a choice of courses (for 24 ECTS), individual projects (for 2+7=9 ECTS), and three **Supplementary** courses (for 18 hours of supervised work in small groups). Each student is guided and mentored by the academic team to prepare for the next phase of their career, aligning with their ambitions.

M2 Program Materials for Sustainable Construction & Environment

Contact: Kamilia Abahri, Associate Professor, ENS Paris-Saclay, LMPS.

The **Materials for Sustainable Construction & Environment** Master 2 program is designed to train future researchers, engineers, and designers in developing and characterizing advanced materials for environmentally responsible construction. The program combines theoretical foundations, experimental practice, and research experience to address the challenges of sustainability and performance in construction materials and systems.

Students gain a multidisciplinary understanding of material behavior under environmental constraints, exploring mechanical, thermal, hydric, and morphological phenomena. Special focus is placed on the degradation mechanisms, damage, durability, and environmental impact of materials, from microstructural processes to structural performance.

Program Objectives:

- Provide a solid theoretical and practical foundation for **research-oriented careers** in sustainable construction materials.
- Cultivate **critical thinking and scientific reasoning** through applied and investigative learning.
- Offer **hands-on research experience** through a supervised internship in a research lab.

Key Skills Acquired:

- Simulate, model, and experiment the behavior (mechanical, thermal, hydric, morphological) of materials and structures in their environment.
- Study advanced materials for sustainable construction and the environment.
- Understand and analyze the degradation and damage mechanisms of these materials, exploring both local and global scales.
- Energy management and sustainable development in construction.
- Propose modern, research-based, and high-level courses.

Semester S1 (from September to January) of this M2 program is organized as follows.

Mandatory courses for a total of 18 ECTS

- Digital Image Correlation and identification (part I) (1.5 ECTS), F. Hild
- Non-linear Finite Element method (3 ECTS), A. Fau
- Coupled energy and mass transfers in porous media (3 ECTS, 24h), R. Bennacer
- Experimental methods (1.5 ECTS), F. Benboudjema
- Low environmental impact materials (3 ECTS, 24h), A. Bourdot
- Durability of construction materials (3 ECTS, 24h), F. Benboudjema
- Thermo-hygro-morphic behavior of materials (3 ECTS, 24h), K. Abahri

Choice of 4 courses for a total of 12 ECTS among the following

- Delayed behavior of construction materials (3 ECTS, 24h), F. Benboudjema
- Thermodynamics of solid materials (part I) (1.5 ECTS), R. Desmorat
- Control of active and reactive systems (part I) (1.5 ECTS), R. Bennacer
- Energy in construction (1.5 ECTS, 12h), R. Bennacer
- Control of active and reactive systems (part II) (1.5 ECTS, 12h), R. Bennacer
- From experiments to modeling and simulation for sustainable construction (1.5 ECTS, 12h), F. Benboudjema
- Énergies éoliennes et marines (1.5 ECTS, taught in French), I. Delbende
- Opening course

M2 Program Computational Methods for Construction Engineering

Contact: Fabrice Gatuingt, Professor ENS Paris-Saclay, LMPS.

The **Computational Methods for Construction Engineering** Master 2 program provides advanced training in numerical modeling, high-performance computation, and data-driven methods applied to Civil Engineering materials and structures. It prepares future researchers and engineers to design, simulate, and optimize complex structural systems exposed to multi-physics, dynamic, and nonlinear phenomena.

Students develop strong theoretical and practical skills in numerical methods, computational mechanics, and scientific computing. The program emphasizes the design and implementation of advanced simulation tools, the use of high-performance computing (HPC), and the integration of machine learning or reduced-order techniques for efficient and accurate prediction of structural behavior.

Program Objectives :

- Train students in state-of-the-art numerical methods for Construction Engineering, including finite element, finite volume, multiscale, and domain decomposition techniques.
- Introduce high-performance computing tools for large-scale structural and fluid simulations.
- Integrate modern data-driven, surrogate, and machine-learning approaches into simulation workflows.
- Ability to model, simulate, and analyze complex structures under multi-physics, nonlinear, or transient conditions.

Key Skills Acquired

- Mastery of high-performance computing techniques for solid and fluid mechanics.
- Implementation and use of advanced numerical methods (finite element, finite volume, multiscale, domain decomposition...).
- Understanding and development of reduced-order and data-driven models, of machine learning methods tailored to construction engineering.
- Proficiency in bridging computational tools with experimental insights when needed.

Mandatory courses for a total of 9 ECTS

- Digital Image Correlation and Identification, part I (1.5 ECTS), F. Hild
- Non-linear Finite Element method (3 ECTS), A. Fau
- Thermodynamics of solid materials, part I (1.5 ECTS), R. Desmorat
- Advanced structural modeling (3 ECTS), F. Gatuingt

Choice of courses for a total of 21 ECTS among the following

- Reduced and surrogate modeling for construction engineering (3 ECTS), A. Fau
- High Performance Computing in Fluid Mechanics (1.5 ECTS), L. Mathelin
- Finite volume and numerical solutions for Navier-Stokes flow (3 ECTS), N. Grenier
- Adaptive models and data-driven approaches (3 ECTS), L. Chamoin
- Multiscale strategies and Domain Decomposition methods (3 ECTS), P.-A. Guidault
- Advanced machine learning for construction engineering (3 ECTS), D. Clouteau
- High Performance Computing in Solid Mechanics (3 ECTS), F. Gatti
- Two Opening Courses

Courses common to the two M2 programs

- Digital Image Correlation and Identification (part I) (1.5 ECTS), F. Hild
- Non-linear Finite Element method (3 ECTS), A. Fau
- Thermodynamics of solid materials (part I) (1.5 ECTS), R. Desmorat
- Coupled energy and mass transfers in porous media (3 ECTS), R. Bennacer
- Control of active and reactive systems (part I) (1.5 ECTS), R. Bennacer
- Delayed behavior of construction materials (3 ECTS), F. Benboudjema
- Thermodynamics of solid materials (part II, porous media) (1.5 ECTS), R. Desmorat

Digital Image Correlation and Identification (part I)

Credits: 1.5 ECTS

Format: 12h of lectures

Contact: F. Hild, Directeur de Recherche CNRS, LMPS, francois.hild@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Mechanics of Materials, finite-element method, statistics, probability theory

Evaluation: written examination (50%), project reports (50%)

Shared by the two programs and partially with Master MAGIS

Course Objectives

- This course is devoted to the introduction of the general principles of Digital Image Correlation (DIC) as an inverse problem. It also deals with the quantification of measurement uncertainties by propagating the acquisition noise to the measured degrees of freedom.
- The students will master the theoretical and implementation aspects of DIC. They will be able to measure displacement fields via DIC, evaluate measurement uncertainties, criticize the results, and choose advanced strategies for performing DIC measurements.

Course Content

Lectures on Digital Image Correlation (DIC)

- Imaging devices (photons, electrons, and all the rest, Atomic Force Microscopy, resolution in space and time, 2D/3D, scanning/full field ...)
- Images (grey-level histograms, encoding depth, color coding, distortions ...)
- Subpixel interpolation (pixel meaning from square box to cardinal splines, all are splines), correlation length, noise
- Optical flow (description of what is conserved in images and what is not). Brightness / Contrast / Temperature / Elevation (Atomic Force Microscopy)
- Kinematic basis (starting from translation and intercorrelation to finite-element)
- Least squares formulation, and numerical solution; 1) gradient descent; 2) multiscale. Discussion on the Hessian matrix (eigenvalue spectrum, eigenmodes)
- Uncertainty quantification, relation with Hessian matrix (motivation for regularization)

Specific challenges and applications of Digital Image Correlation for Civil Engineering structures, mini-structures, and specimens

Examples will illustrate the applications of DIC in civil engineering, particularly for the detection and quantification of damage.

Bibliography

- *Mesures de champs et identification en mécanique des solides*, M. Grédiac, F Hild, Hermes science, 2011.
- *Full-field measurements and identification in solid mechanics*, M. Grédiac, F. Hild, John Wiley & Sons, 2012
- *Comprehensive full-field measurements via Digital Image Correlation*, S. Roux, F. Hild, in V. Silberschmidt (Edt.). *Comprehensive Mechanics of Materials*, 2, Elsevier, pp. 3-56, 2024.

Non-linear Finite Element method

Credits: 3 ECTS

Format: 24h of lectures

Contact: A. Fau, Assistant Professor, ENS Paris-Saclay, LMPS,
amelie.fau@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Linear finite-element method, mechanics of materials for non-linear behavior, fundamentals of transfer, fundamentals of numerical methods (numerical integration, interpolation, and solving a linear system)

Evaluation: Project (50%) + Final written examination (50%)

Shared by the two programs

Course Objectives

This course introduces the application of the finite-element method for the numerical prediction of the response of a structure composed of materials with non-linear constitutive behavior. Students learn how to derive the algorithm for any material behavior systematically. The course emphasizes conceptual development for a variety of non-linear constitutive equations. Thermal and mechanical applications are considered. Various temporal schemes are studied to solve evolution equations.

By the end of the course, students are able to derive their own non-linear finite element program for the material behavior of interest.

Course Content

- Architecture of a finite-element program for non-linear behavior
- Consistent tangent operator
- Explicit and implicit time integration for the evolution equations
- Application to non-linear thermal transfer
- Application to elasto-plasticity
- Application to continuum damage mechanics
- Individual projects for own implementation

Bibliography

- *E.A. de Souza Neto, D. Peric, D.R.J. Owen, Computational Methods for Plasticity: theory and applications, 2008.*

Thermodynamics of Solid Materials (part I)

Credits: 1.5 ECTS

Format: Lectures 12h

Contact: R. Desmorat, Professor ENS Paris-Saclay, LMPS,
rodrique.desmorat@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Continuum Mechanics, elasticity, anisotropy, tensor calculus.

Evaluation: written examination (100%)

Shared by the two programs and with Master GEO2 & Master MAGIS

Course Objectives

- The primary objective is to derive, within a thermodynamic framework that incorporates internal variables, the constitutive equations that describe the mechanical behavior of solids and soils throughout their lifetime.
- By the end of the course, students will have mastered three-dimensional formulations of elasto- (visco-) plasticity models.

Course Content

The thermodynamics of irreversible processes is presented for solid materials, starting from thermo-poroelasticity up to the framework of standard generalized materials. Associated and non-associated elastoplasticity models are described in a general manner, applicable to both metals and geomaterials.

- Shear/hydrostatic elastic energy density, deviatoric/hydrostatic stress, von Mises stress, anisotropy.
- State variables, poro-elasticity.
- 3D visco-elasticity (elastic energy density, dissipation potential, viscosity larger for shear moduli than for bulk modulus) as a toy model for general constitutive equations.
- Thermodynamics of solid materials: 1st and 2nd principle of thermodynamics, Clausius-Duhem Inequality, intrinsic dissipation.
- Local state method, internal variables (including isotropic and kinematic hardening state variables).
- Infinitesimal strain framework of standard generalized materials (associated / non-associated models), positivity of the intrinsic dissipation, heat equation for local states described by internal variables.
- Associated elasto-plasticity: elasto-plasticity of metallic materials, elasto-plasticity of soils and rocks, poro-elasto-plasticity.

Bibliography

- *J. Lemaitre, J.-L. Chaboche, Mechanics of Solid Materials, Cambridge University Press, 1991 (3rd Edition in French 2020).*

Coupled energy and mass transfers in porous media

Credits: 3 ECTS

Format: 24h of lectures

Contact: R. Bennacer, Professor ENS Paris-Saclay, LMPS,
rachid.bennacer@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Thermodynamics, heat transfer, and fluid mechanics; Basic numerical methods; Fundamentals of materials science or environmental processes

Evaluation: Continuous assessment (50%) – assignments, reports, project work; Final exam (50%) – written or oral examination

Shared by the two programs and with Master GEO2

Course Objectives

This course provides an advanced understanding of heat, mass, and momentum transfer in porous and composite materials. It combines theoretical, modeling, and experimental approaches to study phenomena such as diffusion, advection, phase change, and interfacial interactions. The course emphasizes the link between micro- and macro-scale processes and develops advanced skills to model, simulate, and optimize multiphase and multiscale systems using computational tools and sustainability-driven design principles. It enables evaluation of material performance, improvement of energy efficiency, safety, and durability, and supports the development of sustainable technologies and resilient infrastructures in renewable energy, building physics, and environmental engineering. Furthermore, the course integrates a research-oriented perspective, fostering expertise in the design, analysis, and validation of innovative experimental setups, numerical models, and theoretical frameworks for investigating complex transport phenomena in porous media, preparing for contributions to cutting-edge scientific research.

Course Content

- Heat and mass transfer in porous and composite materials
- Diffusion, advection, and phase change mechanisms
- Sorption, capillarity, condensation, and chemical coupling
- Governing equations and constitutive relationships
- Multiphase modeling and micro–macro coupling
- Thermodynamic equilibrium and non-equilibrium processes
- Applications: insulation, energy storage, drying, geothermal systems, and remediation

Learning Outcomes

Students will be able to:

- Formulate and analyze transport equations in porous media.
- Model multiphase and multiscale processes.
- Link micro- and macro-scale phenomena to optimize systems.
- Evaluate energy and environmental system performance.
- Propose sustainable, efficient engineering solutions.

Bibliography

- Nield & Bejan – *Convection in Porous Media* (Springer)
- Kaviany – *Principles of Heat Transfer in Porous Media* (Springer)
- Whitaker – *The Method of Volume Averaging* (Kluwer)

- Bennacer, R. – Research articles on heat/mass transfer and sustainability.

Control of active and reactive systems (part I)

Credits: 1.5 ECTS

Format: 12h of lectures

Contact: R. Bennacer, Professor ENS Paris-Saclay, LMPS,
rachid.bennacer@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Basic modeling of mechanical and energy systems; Elementary thermodynamics, heat transfer, or fluid mechanics (recommended);

Evaluation: Continuous assessment (50%) – assignments, reports, project work; Final exam (50%) – written or oral examination

Shared by the two programs and with Master PIE

Course Objectives

This course introduces the theoretical and practical fundamentals of active and reactive systems that adapt to time-varying conditions. It covers the principles of dynamic system behavior, system stability, regulation, and feedback control. Students learn how system components interact and respond to changes in boundary conditions and external inputs. The course emphasizes conceptual understanding of optimization strategies, control law design, and the theoretical foundations necessary for modeling adaptive systems, preparing for more advanced control applications in *Control of active and Reactive Systems - Part II*.

Course Content

- Introduction to controlled energy, mechanical, and transport systems
- Dynamic responses and stability analysis of active and reactive systems
- Principles of feedback and basic optimization
- Coupling of system components under varying boundary conditions
- Case studies: adaptive building systems, active damping, and others
- Research perspectives: design and validation of adaptive strategies

Learning Outcomes

Students will be able to:

- Describe active and reactive system behavior under dynamic conditions;
- Understand feedback, stability, and basic optimization principles;
- Analyze system responses to changing environments;
- Identify applications for adaptive strategies in engineering systems.

Bibliography

- Åström, K.J., Murray, R.M. – Feedback Systems: An Introduction for Scientists and Engineers, Princeton University Press
- Ogata, K. – Modern Control Engineering, Prentice Hall
- Bennacer, R. – Selected research articles on adaptive control and energy system optimization

Delayed behavior of construction materials

Credits: 3 ECTS

Format: Lectures 24h

Contact: F. Benboudjema, Professor ENS Paris-Saclay, LMPS,
farid.benboudjema@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Recommended to have followed “Coupled energy and mass transfers in porous media”, “Thermodynamics of solid materials – part II porous media”, and “Continuum damage mechanics for quasi-brittle materials”.

Evaluation: Exam

Shared by the two programs

Course Objectives

This course deals with the delayed behavior of construction materials under both environmental (relative humidity, temperature) and mechanical loadings from early age to long-term (hydration, shrinkage, creep). The experimental behavior and the role of the formulation are studied. Chemo-physical mechanisms and existing models are developed to predict material behavior.

- Understand the mechanisms of hydration, shrinkage, and creep in relation to the mix design and the ambient conditions
- Model the early-age and long-term behavior of cement-based materials:
- Analyze the cracking risk by shrinkage restraint through analytical calculations and numerical simulations

Course Content

- Hydration and heat release
- Development of the microstructure and physical/mechanical properties
- Autogenous and drying shrinkage
- Basic and drying creep
- Modelling of thermal, chemical, hydric, and mechanical behavior at early-age and long-term

Bibliography

- Ollivier J.-P., Torrenti J.-M., Carcasses M. (2012) Physical Properties of Concrete and Concrete Constituents, Wiley
- Benboudjema F., Carette J., Delsaute B., Honorio de Faria T., Knoppik A., Lacarrière L., Neiry de Mendonça Lopes A., Rossi P., Staquet S. (2018), Chapter 4, «Mechanical properties », dans Thermal Cracking of Massive Concrete Structures, Rilem Technical Committee CMS, Springer International Publishing, ISBN 978-3-319-76617-1, 2019

Thermodynamics of Solid Materials (part II, porous media)

Credits: 1.5 ECTS

Format: Lectures 12h

Contact: R. Desmorat, Professor ENS Paris-Saclay, LMPS, rodrique.desmorat@ens-paris-saclay.fr

Instructor: R. Desmorat

Language of instruction: English

Prerequisites: Thermodynamics of irreversible processes, three-dimensional elasto-(visco)plasticity.

Evaluation: written examination (100%)

Shared by the two programs

Course Objectives

- The students will master the three-dimensional, nonlinear material models used for the design of 3D Civil Engineering structures and/or soils subjected to complex loadings.
- Specific constitutive equations are detailed, with a focus on non-isothermal loading conditions and poro-elasto-plasticity. The positivity of the intrinsic dissipation and the fulfillment of the second principle of thermodynamics are checked systematically.

Course Content

- Chimio-elasticity, early age concrete.
- Third invariant, Lode angle, general expression of an isotropic criterion function
- Rankine, Hershey-Hosford, (Modified-)Mohr-Coulomb, Willam-Warnke, Mazars criterion functions.
- Marigo (1981) damage model and Lemaitre-Mazars (1980, 1984) damage model for concrete.
- Non associated elasto-plasticity: dilatancy of geo-materials, Drucker-Prager and Willam-Warnke elasto-plasticity.
- Plastic modulus, tangent operator for rate independent Drucker-Prager plasticity.
- Poro-elasto-plasticity, drained and undrained tangent operators.
- Elasto-visco-plasticity of soils.

Bibliography

- *J. Lemaitre, J.-L. Chaboche, Mechanics of Solid Materials, Cambridge University Press, 1991 (3rd Edition in French, 2009).*
- *J. Lemaitre, Materials Behavior Models, Volume III: Multiphysics Behaviors, Academic Press (2001).*
- *O. Coussy, Poromechanics, Wiley, Edition Technip (2004).*

Courses for M2 program

“Modeling & Computing for Construction Engineering”

- Digital Image Correlation and Identification (part II) (1.5 ECTS), F. Hild
- Structures subjected to transient loads (3 ECTS), F. Gatuingt
- Reduced and surrogate modeling for construction engineering (3 ECTS), A. Fau
- Continuum Damage Mechanics for quasi-brittle materials (3 ECTS), R. Desmorat
- Advanced structural modeling (3 ECTS), F. Gatuingt
- Advanced formulations of rational mechanics & its coupling (3 ECTS), R. Desmorat
- Statistical learning for material and structural design (3 ECTS), D. Cluteau

Digital Image Correlation and Identification (part II)

Credits: 1.5 ECTS

Format: 12h of lectures

Contact: F. Hild, Directeur de Recherche CNRS, LMPS,
francois.hild@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: To have followed “Digital Image Correlation and Identification (part I)”

Evaluation: written examination (50%), project reports (50%)

Partially shared with M2 MAGIS

Course Objectives

The course integrates research-oriented procedures dealing with advanced DIC techniques, such as mechanical regularization for robust DIC, space-time DIC, multiview and multimodal correlation for 3D surface and volumetric analyses. The students will also learn how to extract model parameters from measured displacement fields, or directly from images via integrated approaches.

Course Content

Lectures on advanced Digital Image Correlation

- Optimal extractor (noise weighting, covariance, ...)
- Optimal Space-time Digital Image Correlation, Poisson noise
- Mechanical regularization
- Multiview correlation

Lectures on identification based on Digital Image Correlation

- Identification using the Finite-Element Method Updating (FEMU)
- Identification using the integrated Digital Image Correlation (iDIC).
- Integrated Digital Image Correlation for Linear Elastic Fracture Mechanics: measurement of the stress intensity factors K_I , K_{II} , supersingular terms

Application to Construction Engineering

The identification of material parameters using temperature / displacement fields is performed via Finite Element Model Updating (FEMU) for heat transfer applications and/or Continuum Damage Mechanics. Different cost functions are discussed, and their relationship to measurement uncertainties is established.

Bibliography

- *Mesures de champs et identification en mécanique des solides*, M. Grédiac, F. Hild, Hermes science, 2011.
- *Full-field measurements and identification in solid mechanics*, M. Grédiac, F. Hild, John Wiley & Sons, 2012
- *Comprehensive full-field measurements via Digital Image Correlation*, S. Roux, F. Hild, in V. Silberschmidt (Edt.). *Comprehensive Mechanics of Materials*, 2, Elsevier, pp. 3-56, 2024.

Structures subjected to transient loads

Credits: 3 ECTS

Format: Lectures 24h

Contact: F. Gatuingt, Professor ENS Paris-Saclay, LMPS,
fabrice.gatuingt@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Continuum mechanics, engineering mathematics, fundamental/advanced
Finite-Element Method

Evaluation: exam 100%

Partially shared with M2 MAGIS

Course Objectives

This course explores the scientific principles governing extreme loads, such as impacts, blasts, fire, and other extreme events, with an emphasis on their effects on structures. Key topics include 3D wave propagation in solids, experimental and numerical modeling techniques, and the behavior of structures under impact and blast conditions. Students will gain theoretical knowledge to analyze and model the dynamic response of structures under extreme conditions.

Course Content

- 3D Wave and Shock wave propagation
- Dynamics experimental tests: Split Hopkinson Bar, spalling experiments, impact and penetration tests.
- Impact structural modeling: simplified approach and Finite-Element modeling
- Physical aspects of explosions and evaluation of their effects on structures: simplified formulations and Finite-Element modeling.
- Structures subjected to fire: phenomenological analysis and thermo-poro-mechanical modeling of concrete spalling
- Numerical methods for interface couplings (fluid–structure interaction) and volumetric couplings (coupled processes in porous media).

Bibliography

- *L. Davison, Fundamentals of Shock Wave Propagation in Solids, Springer, 2008*
- *M.Y.H. Bangash, Shock, Impact and Explosion: Structural Analysis and Design, Springer, 2009.*

Reduced and surrogate modeling for construction engineering

Credits: 3 ECTS

Format: 24h of lectures

Contact: A. Fau, Assistant Professor ENS Paris-Saclay, LMPS,
amelie.fau@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: mechanics of materials, non-linear finite element method, fundamentals of structural dynamics

Evaluation: 100% final exam

Dedicated to the Program

Course Objectives

Nonlinear finite element analyses often entail high computational costs, particularly in realistic civil, mechanical, and thermal engineering applications. To enable efficient parametric studies and large-scale simulations, model order reduction (MOR) and surrogate modeling techniques have emerged as essential tools for reducing computational complexity while preserving the essential features of the underlying physical phenomena.

The course emphasizes both the mathematical foundations and computational implementation of reduced-order and surrogate models, with particular focus on their application to computational solid mechanics and structural dynamics.

Students will gain the ability to develop, implement, and critically assess model-order reduction and surrogate modeling strategies designed to address high-fidelity problems at reduced computational cost, while developing awareness of the theoretical limitations and practical challenges inherent to these approaches.

Course Content

- Parametrized partial differential equations (PDEs) and the challenges of their finite element approximation. Motivation of reduced-order and surrogate modeling (real-time, high-dimension, multi-query)
- Traditional engineering approaches
- Various reduced-order and surrogate modeling methods, such as Proper Orthogonal Decomposition, reduced basis methods,

Bibliography

- *B. Haasdonk: Reduced Basis Methods for Parametrized PDEs - A Tutorial Introduction.*
- *F. Chinesta et al.: Model Order Reduction, Encyclopedia of Computational Mechanics.*

Continuum Damage Mechanics for quasi-brittle materials

Credits: 3 ECTS

Format: Lectures 24h

Contact: R. Desmorat, Professor ENS Paris-Saclay, LMPS,
rodrigue.desmorat@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Continuum Mechanics, elasto-plasticity, thermodynamics of irreversible processes

Evaluation: Written examination

Dedicated to the Program

Course Objectives

- The main objective is to derive, in the thermodynamics framework of Continuum Damage Mechanics, three-dimensional constitutive equations for quasi-brittle materials such as concrete.
- The student will become fluent in Continuum Damage Mechanics. They will acquire the necessary insight to propose relevant tests and procedures for identifying the material parameters.

Course Content

Three-dimensional isotropic (scalar) damage models are first described, such as those proposed by Marigo and Mazars. These models will be criticized from the points of view of both thermodynamics soundness and representativity of multiaxial responses of cementitious materials.

The question of the tensorial nature of damage is then addressed. Effective stresses are defined, and the principle of strain equivalence is used to couple both elasticity and (visco-)plasticity with damage. A sound thermodynamics formulation of the loading-induced damage anisotropy of quasi-brittle materials is then provided.

- Sought properties of a damage variable
- Effective stress concept (1D, 3D, isotropic damage, anisotropic damage).
- First damage models (Marigo 1981, Lemaitre-Mazars 1980, Mazars 1984).
- Thermodynamics of damage, on the difficulties of ensuring the positivity of the intrinsic dissipation in Continuum Damage Mechanics.
- Loading-induced anisotropic damage of quasi-brittle materials such as concrete.
- Permanent strains due to damage, coupling or not coupling with (visco-)plasticity
- Elements of modeling of cyclic mechanical responses of quasi-brittle materials.
- Visco-damage.
- Quasi-implicit numerical schemes for anisotropic damage models.
- Nonlocal, Eikonal Nonlocal, Gradient damage models, Phase field regularization.

Bibliography

- *J. Lemaitre, A course on damage mechanics, Springer Verlag, 1992.*
- *J. Lemaitre, R. Desmorat, Engineering damage mechanics: ductile, creep, fatigue and brittle failures, Springer, 2005.*
- *J. Lemaitre, J.-L. Chaboche, R. Desmorat, A. Benallal, Mécanique des matériaux solides, 3e éd. 2020.*

Advanced structural modeling

Credits: 3 ECTS

Format: Lectures 24h

Contact: F. Gatuingt, Professor ENS Paris-Saclay, LMPS,
fabrice.gatuingt@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Fundamentals/advanced Finite-Element Method, background in structural modeling, Engineering mathematics

Evaluation: exam 100%

Shared with master GEO2

Course Objectives

Built on the bases of engineering mathematics, mechanics, and structural analysis, the course “Advanced Structural Modeling” enables students to meet the growing challenges of modeling complex civil constructions up to failure.

By the end of the course, students will have the expertise to apply sophisticated numerical models that represent the mechanical degradation of Construction Engineering structures in both research and professional settings.

Course Content

This course focuses on the advanced application of the finite element method and non-linear material constitutive models in Construction Engineering. Emphasis is placed on the assessment of resilience under complex loading, up to failure. Key topics include simplified modeling approaches, advanced finite-element techniques, and resilience assessment methods tailored to extreme loading scenarios.

- Multi-fiber beam finite element
- Crack modeling in finite-element simulations of quasi-brittle material and structures: continuous damage model, embedded discontinuities, discrete elements
- Multiscale modeling
- Measures of Robustness and Resilience of structures: Risk-Oriented, Reliability-Based, Energy-Based, Accumulative Damage models... resilience Measures.

Bibliography

- de Borst R., “Fracture and damage in quasi-brittle materials: A comparison of approaches”, *Theoretical and Applied Fracture Mechanics*, 2022
- Bodnar B., Larbi W., Titirla, M., Deü J.-F., Gatuingt, F., Ragueneau F., “Hyper-reduced order models for accelerating parametric analyses on reinforced concrete structures subjected to earthquakes”, *Computer-Aided Civil and Infrastructure Engineering*, 2024
- Desmorat R., Gatuingt F. and Ragueneau F., “Non-standard thermodynamics framework for robust computations with induced anisotropic damage”, *Int. J. Damage Mechanics.*, 2010.
- Kotronis P, Davenne L & Mazars J (2004). *Poutre multifibre Timoshenko pour la modélisation de structures en béton armé. Revue Française de Génie Civil*, 2004.

Advanced formulations of rational mechanics & its coupling

Credits: 3 ECTS

Format: Lectures 24h

Contact: R. Desmorat, Professor ENS Paris-Saclay, LMPS,
rodrique.desmorat@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Continuum Mechanics

Evaluation: Written examination

Dedicated to the Program

Course Objectives

- The main objective is to introduce advanced geometry concept (Riemannian geometry, exterior calculus...) to formulate modern Continuum Mechanics and its coupling with electromagnetism.

Course Content

- Geometric reformulation of Continuum Mechanics: configurations as embedding, the body as a manifold with border, stresses as powers/1-forms. Strain rate, finite strain, and stress tensors defined by pullback/pushforward operations.
- Conservation laws are formulated using the Lie derivative.
- Differential forms, and their application to modern 4D formulation of electromagnetism.
- Primary and secondary field variables in physics and mechanics, a general Lagrangian framework for couplings formulation, and elements of variation calculus.

Bibliography

- Kolev B., Desmorat, R., *An intrinsic geometric formulation of hyper-elasticity, pressure potential and non-holonomic constraints*, *Journal of Elasticity*, 146(1), 29-63, 2021.
- Kolev B., Desmorat, R., *Objective rates as covariant derivatives on the manifold of Riemannian metrics*, *Archive for Rational Mechanics and Analysis*, 248(4), 66, 2024.
- Kolev K., *Éléments de géométrie différentielle à l'usage des mécaniciens*. 2020. hal-03330418

Statistical Learning for Material and Structural Design

Application to Construction Engineering

Credits: 3 ECTS

Contact: D. Clouteau, Professor CentraleSupélec, LMPS,
didier.clouteau@centralesupelec.fr

Language of instruction: English

Prerequisites: Probability theory, Continuum Mechanics, Structural analysis

Evaluation: written examination (50%) and project report (50%).

Course Objectives

Unlike traditional deterministic design methods, which rely on fixed safety factors, probabilistic approaches explicitly account for uncertainty in loads, material properties, geometry, and environmental conditions. Students will learn how to quantify, model, and manage these uncertainties to make more informed and resilient engineering decisions.

In particular, this course explores how probabilistic mechanics and machine learning are combined to enhance risk assessment, reliability analysis, and decision-making in civil engineering. Traditional deterministic design approaches are being transformed by data-driven methods that can better capture uncertainty, complexity, and interdependence in infrastructure systems. Students will learn to apply probabilistic and machine learning techniques to predict performance, assess risk, and support resilient, adaptive engineering design.

- This course reviews the fundamentals of probability, statistics, and information theory to account for Uncertainty Modeling, Quantification, and Propagation in structural and material mechanics
- Reliability analysis for non-linear response.
- Statistical and Machine learning to build efficient surrogate models for structures or materials, taking advantage of extensive databases originating from either advanced experiments or numerical simulations.

Course Content

- Review of the fundamentals of probability theory: random variables, information entropy, estimation, statistical analysis, stochastic fields
- Probabilistic modeling tools and uncertainty propagation methods, polynomial chaos, Monte Carlo simulation
- Description of random fields from Karhunen-Loève expansion, parametric studies from kriging approaches
- Machine learning: supervised learning for classification and regression, stochastic gradient, universal approximation theorem, two-layer neural networks, deep networks and convolutional networks, unsupervised and semi-supervised learning, autoencoders, generative adversarial networks (GANs)
- Risk assessment by combining a probabilistic approach and machine learning
- Application to a nonlinear structural response in civil engineering.

Bibliography

- G. Stefanou, *The stochastic finite element method: Past, present and future*, 2009
- B. Sudret, A. Der Kiureghian. *Stochastic finite element methods and reliability. A state-of-the-art report*, 2000.

Courses for M2 program

“Materials for Sustainable Construction & Environment”

- Experimental methods (1.5 ECTS), F. Benboudjema
- Low environmental impact materials (3 ECTS), A. Bourdot
- Durability of construction materials (3 ECTS), F. Benboudjema
- Thermo-hygro-morphic behavior of materials (3 ECTS), K. Abahri
- Energy in construction (1.5 ECTS), R. Bennacer
- Control of active and reactive systems (part II) (1.5 ECTS), R. Bennacer
- From experiments to modelling and simulation for sustainable construction (1.5 ECTS), F. Benboudjema
- Reduced models for transient thermal problems (3 ECTS), O. Quemener
- Énergies éoliennes et marines (1.5 ECTS, taught in French), I. Delbende

Experimental methods

Credits: 1.5 ECTS

Format: 6h of lectures, 10h of practical class

Contact: F. Benboudjema, Professor ENS Paris-Saclay, LMPS,
farid.benboudjema@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: microstructure of cement-based materials, fundamentals of statistics

Evaluation: Final exam + practical work

Course Objectives

This course explores various experimental techniques for civil engineering materials in relation to their durability from the microscopic to the material scale. Microstructural analysis (mineral phases, liquids, and porosity) testing devices used in research applications, such as Scanning Electron Microscope (SEM), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), X-ray tomography, Mercury Intrusion Porosimetry (MIP), are described and analyzed. Sensors for measuring temperature, relative humidity, pressure, and other parameters are also studied. The effects of Representative Elementary Volume (REV), material parameter variability, and sensor uncertainties are discussed.

Course Content

- Presentation and discussion on experimental characterization of microstructure and porosity of construction materials: SEM, XRD, TGA, X-ray tomography, MIP.
- Analysis of research experimental devices for diffusion and permeation in reactive porous materials.
- Sensor principles used in thermal, diffusion, and permeation.
- Analysis of real experimental results: influence of Representative Elementary Volume (REV), material parameters variability, and sensors uncertainties
- Practical works undertaken by the students include durability analysis, accelerated chloride diffusion, permeation, and micromorphology.

Bibliography

- *V.S. Ramachandran, James J. Beaudoin, Handbook of Analytical Techniques in Concrete Science and Technology, William Andrew Publishing, 2001, ISBN 9780815514374.*
- *Nicolas BURLION, "Test techniques and experimental characterization", edited by Jean-Michel Torrenti, Gilles Pijaudier-Cabot and Jean-Marie Reynouard, Wiley, 2010, p. 3-55.*

Low environmental impact materials

Credits: 3 ECTS

Format: 24h of lectures,

Contact: A. Bourdot, Assistant Professor ENS Paris-Saclay, LMPS,

alexandra.bourdot@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Eco-conception, on Life Cycle Analysis, on durability of materials, and to have followed the two M2 courses “Durability of building materials” & “Coupled energy and mass transfers in porous media”.

Evaluation: 80% Exam (3h) + 20% Presentation

Course Objectives

- This course fits into the sustainable development goals by examining the reduction of the environmental impact of construction through the viewpoint of materials. The objective of current research is to obtain new materials that do not require clinker to form a cement paste, to recycle steel and concrete from demolition, and to recover waste or end-of-life products.
- An introduction to the impact of civil engineering, the challenges and solutions for reducing the sector's carbon footprint will provide an understanding of current and future issues. Then, the course proposes for the student an overview of the eco-friendly materials with regard to their properties (thermophysical, chemical, mechanical, and hydric properties...), their potential applications in civil engineering and construction projects (new building, renovation, and rehabilitation), and their LCA or carbon impact. The course will cover concepts of mechanics and structure, delayed behavior and durability, transfers in porous media, and the physico-chemistry of reactions.

Course Content

Topics covered include:

- Environmental impact of construction: current situation, challenges, solutions.
- Mineral and bio-based additions and substitutions for binders to reduce the use of clinker, which has a high carbon impact;
- Concretes made from alternative and recycled aggregates; waste from deconstruction is a major issue for construction and roads,
- The management of sediments and products from aquaculture
- Wood as an element of sustainable development; and the use of renewable energies
- Steels: structural value, recycling, and carbon impact.
- Lightweight materials for building comfort.

Bibliography

- *F.P. Torgal, S. Jalali, Eco-efficient Construction and Building Materials, 2011*
- *S. Amziane, M. Sonebi, Bio-Based Building Materials, Trans Tech Publications Ltd, 2022*
- *F. Orsini, P. Marrone, Approaches for a low-carbon production of building materials: A review. Journal of Cleaner Production, 2019*

Durability of construction materials

Credits: 3 ECTS

Format: 24h of lectures

Contact: F. Benboudjema, Professor ENS Paris-Saclay, LMPS,
farid.benboudjema@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Recommended to have followed M2 course “Coupled energy and mass transfers in porous media”.

Evaluation: Final exam (100%)

Course Objectives

This course deals with the prediction of durability of building construction materials and structures. Main chemical attacks are analyzed in regard to environmental conditions (temperature, relative humidity and chemical environments) and material mix design: carbonation, chloride and (internal and external) sulphatic attacks, Alkali-silica reaction and leaching. Chemo-physical mechanisms from the nanostructure to the mesoscopic scales are detailed, in relation to their effects on the structure level. Experiments, multiscale and Multiphysics modeling approaches and design recommendations are analyzed and discussed.

Course Content

- Presentation and discussion on chemo-physical mechanisms controlling the durability of reinforced concrete structures
- Analysis of the effects of temperature, relative humidity, chemical environment and mix design on the main pathologies of concrete and rebar
- Laboratory and in-situ experimental measurements (destructive and nondestructive techniques)
- Modelling of transport phenomena regarding leaching, CO₂, chloride and sulfate transports, internal swelling
- Analysis of the structural behavior of degraded reinforced concrete structures due to internal swelling

Bibliography

- *Marios Soutsos, ICE Handbook of Concrete Durability. A practical guide to the design of resilient concrete structures, ICE Publishing, 576 pages*
- *Kefei Li, Durability Design of Concrete Structures, 2016 John Wiley & Sons Singapore Pte. Ltd.*

Thermo-hygro-morphic behavior of materials

Credits: 3 ECTS

Format: 20h of lectures, 4h of practical class

Contact: K. Abahri, Associate Professor, ENS Paris-Saclay, LMPS,

kamilia.abahri@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: heat transfer, thermodynamics of materials, basic image processing

Evaluation: written exam

Course Objectives

- The course aims to study, through innovative approaches, the hygro-morphic behavior in porous materials in general and bio-based materials in particular. Several scales of observation are considered, from the cell wall scale of the plant component of these materials to the envelope scale.
- In terms of modeling, the aim is to improve current knowledge of existing models by considering the real 3D morphology of the material, including its hygro-morphic behavior. Particular attention is devoted to integrating the hysteresis phenomenon and the dimensional variation of the materials.

Course Content

- Part 1: Multiscale Thermo-Hygro-Morphic Behavior
The first part of the course focuses on the physical mechanisms and multiscale interactions governing the thermo-hygro-morphic behavior of porous and bio-based materials. The lectures address the coupling between heat, moisture, and deformation processes, as well as the influence of material structure and morphology across different observation scales. Special attention is given to the impact of these coupled phenomena on material aging and biodeterioration, highlighting how environmental conditions accelerate degradation and alter performance over time. Emphasis is placed on understanding experimental characterization methods and their integration into predictive models.
- Part 2: Morphological Characterization and Numerical Simulation
The practical sessions introduce digital tools for analyzing and simulating the behavior of real materials. Students first use ImageJ to perform morphological analysis of material microstructures (e.g., porosity, texture, orientation). Based on these results, a 3D simulation using COMSOL Multiphysics is carried out to model the thermo-hygro-morphic responses on an actual material geometry.

Bibliography

- Rima A., Abahri K., Bennai F., El Hachem & Bonnet M. (2021). *Microscopic estimation of swelling and shrinkage of hemp concrete in response to relative humidity variations*, *Journal of Building Engineering*
- Kosiachevskiy D., El-Hachem C., Abahri K., Bennacer R. & Chaouche M. (2021). *Biomaterials heterogeneous displacement, strain and swelling under hydric sorption/desorption: 2D image correlation on spruce wood*, *Construction and Building Materials*
- El Hachem C., Abahri K., Leclerc S. & Bennacer R., (2020). *NMR and XRD quantification of bound and free water interaction of spruce wood fibers*, *Construction and Building Materials*

Energy in construction

Credits: 1.5 ECTS

Format: 12h of lectures

Contact: R. Bennacer, Professor ENS Paris-Saclay, LMPS,
rachid.bennacer@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Fundamentals of thermodynamics and heat transfer; Basic building physics and materials science; Elementary knowledge of renewable energy systems (recommended)

Evaluation: Continuous assessment (50%) – assignments, reports, project work; Final exam (50%) – written or oral examination

Course Objectives

This course provides an advanced understanding of building energy performance, with a focus on thermal dynamics, energy efficiency, and integration of renewable energy systems. It combines theoretical and applied perspectives on heat transfer, thermodynamic behavior of building envelopes, and dynamic interactions between building components and environmental conditions. The course investigates strategies to achieve net-zero or energy-positive buildings, including passive cooling, free cooling, thermal storage, and active energy management. Emphasis is placed on modeling, simulation, and optimization of energy flows, integrating component-level efficiency with system-level performance, and evaluating the interactions between renewable energy sources and building operation. The course also adopts a research-oriented approach, enabling students to develop scientific expertise in the analysis, design, and performance evaluation of sustainable building systems.

Course Content

- Thermodynamic behavior of building envelopes and high-performance components, including multi-layered insulation and glazing
- Passive and hybrid strategies: free cooling, natural ventilation, thermal mass, daylighting, and energy management
- Integration of renewable energy systems and energy storage for net-zero and positive-energy objectives
- Modeling, simulation, evaluation, and research applications in sustainable and energy-positive building systems

Bibliography

- *Fabbri, K., et al. – Energy Efficiency in Buildings, Springer*
- *Bennacer, R. – Selected research articles on building energy performance and renewable integration*

Control of active and reactive systems (part II)

Credits: 1.5 ECTS

Format: 12h of lectures

Contact: R. Bennacer, Professor ENS Paris-Saclay, LMPS,
rachid.bennacer@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Basic numerical methods and simulation tools; Completion of Part I;
Dynamics and control theory (recommended);

Evaluation: Continuous assessment (50%) – assignments, reports, project work; Final exam (50%) – written or oral examination

Course Objectives

This part (II) emphasizes advanced theoretical and applied aspects of active and reactive systems. It covers modeling of dynamic multi-physics systems, predictive, adaptive, and robust control strategies, and stability analysis under time-varying boundary conditions. The course develops skills in optimization of building system components and material responses, integrating control theory with energy, mechanical, and transport processes. It fosters research-oriented expertise in designing, simulating, and validating complex control strategies, bridging theory with practical applications in engineering and smart infrastructure.

Course Content

- Advanced modelling and simulation of controlled energy, mechanical, and transport phenomenon
- Optimization of component parameters and material responses under dynamic conditions
- Coupling control with heat, mass, and energy transfer processes
- Stability analysis and design of predictive, adaptive, and robust control laws
- Case studies: adaptive building systems, active damping,
- Research applications: design and validation of innovative control strategies for multi-physics systems

Learning Outcomes

Students will be able to:

- Model and simulate active and reactive systems using advanced theoretical and computational tools;
- Apply predictive, adaptive, and robust control strategies;
- Optimize system performance under dynamic conditions;
- Integrate control with energy and mechanical system design;
- Contribute to research and innovation in adaptive and resilient engineering systems.

Bibliography

- Åström, K.J., Murray, R.M. – *Feedback Systems: An Introduction for Scientists and Engineers*, Princeton University Press
- Ogata, K. – *Modern Control Engineering*, Prentice Hall
- Bennacer, R. – *Selected research articles on adaptive control and energy system optimization*

From experiments to modelling and simulation for sustainable construction

Credits: 1.5 ECTS

Format: 12h of lectures

Contact: F. Benboudjema, Professor ENS Paris-Saclay, LMPS,
farid.benboudjema@ens-paris-saclay.fr

Language of instruction: English

Prerequisites: Experimental methods, durability, life cycle analysis, cement-based materials microstructure, modelling of transport phenomena in porous materials (energy and mass), numerical methods

Evaluation: Project report and presentation

Course Objectives

The objectives of this course are to apply the skills acquired in the field of experimental methods and modeling of transport phenomena in porous materials, as well as in the field of numerical methods. The experimental results (permeability and ion diffusion) obtained during the practical work in the experimental methods module will be used to predict the lifespan of a reinforced concrete structure (bridges, nuclear power plants, dams, etc.). A model will be developed by proposing hypotheses on transport mechanisms and analyzing boundary conditions. The solution of parabolic partial differential equations in the linear and nonlinear domains will be implemented. A multi-criteria analysis (including price and environmental impact factors such as greenhouse gas emissions and resource depletion) will be conducted to determine the optimal geometry and composition of the material to be used.

Course Content

- Analysis of experimental results in steady state and transient conditions. Identification of material parameters (diffusivity, permeability).
- Several projects will be proposed to students, and each group will choose a topic.
- Proposal of an ionic (chlorides) or gaseous (CO₂) diffusion model taking into account porosity, then composition parameters. Numerical implementation in the linear and then the nonlinear case. Multi-criteria analysis to identify the optimal composition and geometry.
- Proposal of a model taking into account liquid water permeation (drying) and gas tightness. Coupling between the two models. Application to a containment building for nuclear reactors to predict its service life.

Bibliography

- Kumar, P. - Mehta – Monteiro, P.: *Concrete Microstructure, Properties, and Materials*, McGraw Hill, third edition, <http://dx.doi.org/10.1036/0071462899>.
- Ababneh A., Benboudjema F., Xi Y., *Chloride penetration in nonsaturated concrete*, *Journal of Materials in Civil Engineering*, ASCE journal, 2003, 2(15), p. 183-191

Reduced models for transient thermal problems

Credits: 3 ECTS

Format: 18h of lectures, 3h of exercise class, and 3h of practical class

Contact: F. Joly

Language of instruction: French

Prerequisites: Basic heat transfer + basic coding

Evaluation: final exam

Course Objectives

- In addition to its obvious applications, heat transfer is omnipresent for the design of systems, whether in thermomechanics or metrology. Its precise consideration involves the numerical solution of the heat equation, which might require significant memory space and computation time. This often prohibits its implementation in the iterative process encountered in inverse problems. These latter aim to determine causes or parameters from observed effects, and are crucial in various scientific and mathematical fields.
- The course is a numerical/code module applied to heat transfer. Its objective is to present modal reduction methods for the numerical solution of the heat equation, as well as their application to inverse problems such as parameter identification.

Course Content

- Part 1: Direct Simulation.
After a brief review of heat transfers, various numerical methods used to solve the heat equation are reviewed, followed by a presentation of modal methods. The course alternates lectures and practical classes during which students implement methods covered in class.
- Part 2: Inverse Problems.
The inverse problem is presented. Using the previously obtained reduced model, the objective is to identify a parameter of the problem, either a material property or a time-varying boundary condition.

Bibliography

- *F. Joly, Y. Rouizi, O. Quéméner, Type of inverse problem, model reduction, model identification, Part B, Advanced Autumn School in Thermal Measurements and Inverse Techniques METTI8, 24-29 September, Ile d'Oléron, France.*

Énergies éoliennes et marines

Crédits: 1.5 ECTS

Format: 6h of lectures, 5h of exercise class and 4h of practical class

Contact: Ivan Delbende

Language of instruction: French

Prérequis: Mécanique des fluides élémentaire (bilans de masse, de quantité de mouvement, d'énergie. Théorème de Bernoulli)

Évaluation: Projet et examen final

Course Objectives

Le cours présente les grands principes, éprouvés ou émergents, sur lesquels les machines de production d'énergie renouvelable éolienne et marine sont conçues, avec un accent mis sur la modélisation en aérodynamique des rotors et sur la prédiction de l'énergie annuelle produite.

- Compréhension et prévision de la conversion mécanique dans une machine de production d'énergie renouvelable éolienne ou marine
- Dimensionnement et design d'une machine de production d'énergie renouvelable éolienne ou marine
- Prévision de l'énergie produite annuellement par une machine de production d'énergie renouvelable éolienne ou marine.

Continuellement remis à jour, il aborde aussi l'actualité très fournie dans ces domaines.

Course Content

- Aérogénération : historique, développement actuel et principes de base
- Éolienne standard : fonctionnement, rendement instantané et production annuelle
- Énergies marines : éolien off-shore, hydroliennes et dispositifs houlo-moteurs

Des études de cas et des dimensionnements sont proposés sous forme d'exercices de TD et d'une séance de TP numérique encadrée.

Bibliography

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