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Syllabus Cursus Master's Degree in Engineering, Mechanics. Sorbonne University CMI5

Solid Mechanics: Materials and Structures (MS2)

List of Teaching Units

Semester 9

Core Units

- Technoscience, ethic and society
- Fracture mechanics
- Non-linear behaviour of solids
- Numerical calculation of non-linear structures
- Introduction to homogenization of continuous media

Modelling and Simulation

- Structural design code practices and app.
- Options 1: Damage / Fatigue / Heterogeneous elasticity and RoW / Multi-scale learning of plasticity
- Options 2: Composites Optimization / Structural stability / Project in non-linear structural analysis

Durability of materials and structures

- Issues of severe nuclear accidents / Seminar Issues of electricity in energy systems
- EPR Physics and Operations
- Identification, in-service monitoring of civil engineering structures and major systems
- Uncertainty engineering in mechanics
- Options : Multi-scale approaches to the plasticity of metals / Durability of concretes / Modelling and simulation of equipment under earthquakes

Multiscale Analysis for Materials and Structures

- Elasticity and strength of heterogeneous materials
- Applied micro-poro-mechanics
- Multi-layer structure Modelling
- Images and mechanics
- Options: Damage / Multi-scale approaches to metal plasticity / Concrete durability / Homogenization calculation at break / Methods for identifying model parameters

Semester 10

- Certification
- Deepening Project
- Graduation internship

		Title Teaching Unit - Master Cycle – CMI5	Code	Lecture	Discussion session	Lab	SSA	Hours Attendance	Work Personal	ECTS
CMI5 S9		Technoscience, ethic and society	MU5EEG03	16	8		24	24	40-60	6*
		Solid Mechanics: Materials and Structures (MS2)								
		Fracture mechanics	MU5MES02	30				30	30	3
		Non-linear behaviour of solids	MU5MES03	30				30	30	3
		Numerical calculation of non-linear structures	MU5MES01	30				30	30	3
		Introduction to homogenization of continuous media	MU5MES04	30				30	30	3
	Thematic elective teachings	**Modelling and Simulation**								
		Structural design code practices and app.	MU5MES08	8		52		60	60	6
		One Option: Damage / Fatigue / Elasticity and heterogeneous RoW / Multi-scale learning of plasticity	MU5MES05/ 07/12/17	30				30	30	3
		One Option: Composites Optimization / Structural Stability / Project in non-linear structural analysis /	MU5MES09/ 10/ 06	30				30	30	3
		Durability of materials and structures								
		Issues of severe nuclear accidents / Seminar Issues of electricity in energy systems	MU5MES18	24				24	30	3
		EPR Physics and Operations	MU5MES21	27				27	30	3
		Identification, in-service monitoring of civil engineering structures and major systems	MU5MES19							3
		Uncertainty engineering in mechanics	MU5MES15	24				24	30	3
		Two options: Multi-scale approaches to the plasticity of metals / Durability of concretes / Modelling and simulation of equipment under earthquakes	MU5MES17/ ??/20	24 24				24 24	30 30	3 3
		Multiscale Analysis for Materials and Structures								
		Elasticity and strength of heterogeneous materials	MU5MES12	24					30	3
		Applied micro-poro-mechanics	MU5MES13	12	6			18	30	3
		Multi-layer structure Modelling	MU5MES14	8		14		22	30	3
		Images and mechanics	MU5MES16	24				24	30	3
		Options: Damage / Multi-scale approaches to metal plasticity / Concrete durability / Homogenization calculation at break / Methods for identifying model parameters	MU5MES05/ 17/??/22/15	24 24				24 24	30 30	3 3
Total Core 12 + 6* ECTS - Total Thematic 18 ECTS - Total - CMI5 S9 MS2 30 ECTS + 6*										

Title Teaching Unit - Master Cycle – CMI5		Code	Lecture	Discussion session	Lab	SSA	Hours Attendance	Work Personal	ECTS
CMI5 S10	TOIC /TOEFL certification	MU4LVANT				30		30-40	3*
	Deepening Project	MU5EEG04				40		50-60	3*
	Graduation internship	MU5MES03					800	80-100	30
Total CMI5 - S10 30 ECTS + 6 *									

*Non-contractual units (not included in the calculation of the semester average (listed in the diploma supplement)

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Semester 9

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Technosciences, Ethic and Society

Level CMI5 - **Semester** S9 - **Credits** 6 ECTS - **Code** MU5EEG03 - Master's **mention**

Pedagogical presentation.
The objective of this course is to bring students to reflect on the social and ethical dimensions of the engineering profession. It focuses on the complex relations between society and technology, and in particular on the role of technology as a value carrier. Based on these analyses, the course then explores the ethical questions and dilemmas that engineers may encounter in the course of their work. Particular attention is paid to examining classic cases in engineering ethics, such as Three Mile Island and the Quebec Bridge. By the end of this course, students will be able to identify ethical issues raised by professional practices. They will also be reflective on their future profession. The course is taught in English.

Content of the Teaching Unit.
- Introduction
- Technical determinism and social construction. Read: T. Pinch and W. Bijker, The Social Construction of Facts and Artifacts? Presentation: (also) Robert Heilbroner, Do Machines Make History?
- Devices, systems, and their power of action on society. Read: B. Latour, Where are the Missing Masses? The Sociology of a Few Mundane Artifacts. Presentation: (also) T. Hughes, Technological Momentum.
- Techniques et valeurs. Lire : J. Wetmore, A. Technology : Reinforcing Values, Building Community. Exposé : (aussi) LangdonWinner, Do Artifacts Have Politics ? et R. Weber, Manufacturing Gender in Commercial and Military Cockpit Design.
- Complexity and uncertainty. Bring: Proposal for a dissertation Read: D. Vinck, Engineers in everyday life. Lecture : (also) JamesonWetmore, Engineering Uncertainty.
- Engineering and experimentation. Read, lecture: M. Martin and R. Schinzinger, Introduction to Engineering Ethics, pp. 77-103.
- Technical disasters. Reading and presentation : S.K.A. Pfaitteicher, Lessons amid the Rubble, pp. 36-61.
- Engineering and security. Reading and presentation : Mike Martin and Roland Schinzinger, Ethics in Engineering, pp. 117-145.
- Engineering and environment. Reading, presentation: Mike Martin and Roland Schinzinger, Ethics in Engineering, pp. 219-242.
- Nanotechnologies, génétique et robotique. Lire: Bill Joy, Why the Future Doesn't Need Us. Exposé : Interagency Working Group on Nanoscience, Engineering, and Technology, Nanotechnology : Shaping theWorld Atom by Atom.

Prerequisite. The corpus of societal and cultural opening lessons of the LECTUREI course followed since the 1st year.

Références bibliographiques. Bowen R. 2012. Engineering Innovation in Health Care : Technology, Ethics and Persons. HRGE, pp. 204-221. Collins, Harry & Trevor Pinch. 2002. The Golem at Large : What You Should Know about Technology. Cambridge University Press. Didier. Ch. 2008. Penser l'éthique des ingénieurs. Paris, PUF. Didier, C.. 2008. Les ingénieurs et l'éthique : pour un regard sociologique. Hermes Science publications. Heilbroner, Robert. 1967. Do Machines Make History? Technology and Culture, pp. 335-345. Hughes, T. 1994. Technological Momentum, in Marx, Leo & Merritt Roe Smith, Does Technology Drive History? The Dilemma of Technological Determinism. Cambridge: MIT Press, pp. 101-113. Interagency Working Group on Nanoscience, Engineering, and Technology, Nanotechnology: Shaping the World Atom by Atom, in Johnson, Deborah et Jameson Wetmore. Technology and Society: Building Our Sociotechnical Future. MIT Press Johnson, D. & Jameson W.. 2008. STS and Ethics: Implications for Engineering Ethics, in Hackett, Edward, Olga Amsterdamska, M. Lynch et J. WajLecturean, The Handbook of Science and Technology Studies. Cambridge, MIT Press, pp. 567-582. Joy, Bill. Avril 2000. Why the Future Doesn't Need Us,Wired, pp. 238-262. Latour, B. 1992. Where Are the Missing Masses? The Sociology of a Few Mundane Artifacts in Wiebe Bijker et John Law, Shaping Technology/Building Society: Studies in Socio-technical Change. Cambridge, MIT Press, pp. 225-258. Martin, Mike & Roland Schinzinger. 2005. Ethics in Engineering. McGraw-Hill. Martin, M. & Roland S.. 2010. Introduction to Engineering Ethics. New York : McGraw- Hill. Pfattaicher, S. K. A. 2010. Lessons Amid the Rubble. Johns Hopkins University Press. Pinch, Trevor & Wiebe Bijker. 1987. The Social Construction of Facts and Artifacts in Wiebe Bijker, Thomas H.,Trevor P., The Social

Construction of Technological Systems. Cambridge, MIT Press, pp. 17-50. Vinck, D. 1999. Ingénieurs au quotidien : ethnographie de l'activité de conception et d'innovation. Presses universitaires de Grenoble. Weber R.. 1997. Manufacturing Gender in Commercial and Military Cockpit Design, Science, Technology, & Human Values, pp. 235-253. Jameson. 2008. Engineering with Uncertainty: Monitoring Air Bag Performance, Science and Engineering Ethics, pp. 201-218. Jameson. 2009. Amish Technology: Reinforcing Values, Building Community in Johnson, D. et Jameson W.. Technology and Society: Building Our Sociotechnical Future. Cambridge: MIT Press. -Winner, Langdon. 1986. Do Artifacts Have Politics? The Whale and the Reactor: a Search for Limits in an Age of High Technology. University of Chicago Press, pp. 19-39.

Resources available to students. Lecture materials. List of books.

Scientific knowledge developed in the unit.

- Knowledge of the social and ethical dimensions of the engineering profession.

Skills developed in the unit.

- Improvement of the knowledge of English. Improvement of written expression.
- Forms of reasoning practiced in the social sciences.

Hourly volumes in and out of the classroom.
Total attendance hours: 24 hours divided into 16 hours of class, 8 hours of discussion sessions. Personal work 40-60 hours.

Evaluation. Attendance at sessions: 20%, Presentation: 20%, Essay: 40%, Essay defence: 20%.

Teacher. C. Lecuyer

Mechanics of brittle fracture

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.

This course aims at exposing the basics of the brittle fracture theory, as it is commonly used in research laboratories and advanced industry (nuclear, aeronautics, ...) to predict and control the cracking of materials. The materials considered are mainly metallic materials for which the students have a good culture (behaviour at the scale of the crystal structure) either via the CMI4 or CMI5 level courses.

Content of the Teaching Unit.

The course includes 2 chapters on basic knowledge and a third one a little more specialized.

- Irwin's theory of KIc.
- Griffith's energy theory.
- Crack propagation in mixed mode.

Prerequisite. Solid Mechanics Master 1 level.
Good bases of practical mathematics (elementary algebra and analysis, differential equations, fonctions of a complex variable, calculations).

Bibliographical references.

- Leblond J. B. , Mechanics of ductile and brittle fracture, Hermes, 2003.
- Griffith A.A., The phenomena of rupture and flow in solide, Philosophical Transactions of the Royal Society of London, série A, vol. 221, 1921, p. 163–198
- E. Erdogan (2000) Fracture Mechanics, International Journal of Solids and Structures, 27, p. 171–183.

Resources available to students.

Course notes and annals.

Scientific knowledge developed in the unit.

- At the end of the EU, the student has the basic tools of brittle fracture mechanics, set out in an exhaustive and detailed manner, enabling him or her either to meet the requirements of a mechanical engineering office or to undertake a thesis in the field.

Skills developed in the unit.

- Calculation of crack propagation in simple cases.

Hourly volumes in and out of the classroom.

Total Attendance Hours: 30 hrs (integrated lectures and discussion sessions): Personal Work 30 hrs.

Evaluation.

The evaluation is based on a written report lasting 3 hours.

Teacher. Mr J.B. Leblond

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Non-linear behaviour of solids

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
Assessment of non-linear behavioural laws in a classical thermodynamic context.

Content of the Teaching Unit.

- Brief reminder of the basic concepts of continuous media mechanics and the various behaviours of structural materials
- Thermomechanical balance laws for continuous media: momentum balance, energy balance and entropy balance. Presentation of Clausius-Duhem inequality and dissipation (intrinsic and thermal)
- Generalized standard materials framework: general method of formulating behavioural laws; role of Clausius-Duhem inequality. Notions of state variables, internal variables, state functions and thermodynamic potentials. Equation of heat. Construction and identification of the main classes of behavioural models: recalls of the fundamental rheological models based on spring, shoe and damper. Case of thermoplastic materials, thermo-viscoelastic materials (Kelvin-Voigt model, Maxwell model)
- Elasto-plasticity and applications: Formulation of perfect elasto-plastic models. Consideration of strain hardening (isotropic and/or kinematic). Thermo-mechanical calculations and simple problem solving of elasto-plastic structures.
- Some notions on laws coupling elasticity and isotropic damage
- Elasto-visco-plastic behaviour. Presentation of some models of time-dependent behaviour; viscosity regulating effect.

Prerequisite. Solid Mechanics Master 1 level.

Bibliographical references.

- H. Ziegler, An introduction to thermoechanics, North Holland, 1983
- P. Germain, Q. S. Nguyen, P. Squat, Continuum Thermodynamics, J. Appl. Mech., ASME 50, 1010-1021, 1983.
- J. Lemaître, J. L. Chaboche, Mechanics of Solids Materials, Cambridge University Press, 1990
- G. Maugin, The thermomechanics of plasticity and fracture, Cambridge University Press 1992
- Q. S. Nguyen, Stability and Nonlinear Solids Mechanics, Wiley, 2000
- M. Fremond, Non Smooth Thermomechanics, Springer Verlag, 2002,
- J. Lubliner, Plasticity Theory. Dover Publications Inc., Mineola, New York, 2008.
- H. Maitournam, Matériaux et Structures inélastiques, Éditions de l'École Polytechnique, 2016

Resources available to students. Annals.

Scientific knowledge developed in the unit.

- Master the modelling of non-linear material behaviours.

Skills developed in the unit.

- Choice of a model for a given use.
- Identification of a complex behavioural law from experimental data provided.

Hourly volumes in and out of the classroom.
Total Attendance Hours: 30 hrs (integrated lectures and discussion sessions): Personal Work 30 hrs.

Evaluation.
The evaluation is based on a written report lasting 3 hours.

Teacher. Mr. D. Kondo

Numerical calculation of solids and non-linear structures

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
The aim of the teaching is to solve nonlinear solid mechanics problems on computer by implementing the finite element method and solving algorithms. Students will be introduced to the use of modern high-performance scientific computing tools (FEniCS, PETSc), visualization tools (paraview) and project management (git).
Content of the Teaching Unit.

- Linear elasticity, variational formulation, discretization: Reminder on how to solve a finite element mechanics problem. Getting to grips with python and FEniCS, Solving an elasticity problem using FEniCS.
- Non-linear elasticity: Non-linear elasticity, linearization, buckling, stability. Solving a problem of non-linear elasticity, buckling and post-buckling.
- Non-linear dynamics: Implicit, explicit methods. Solving problems of nonlinear dynamics.
- Project: working on a project in pairs.

Prerequisite. Mechanics of environments continus - Knowledge of a programming language (ideally python), - Basic course on finite elements and numerical methods

Bibliographical references.

- Belytschko T., Liu W. K. and Moran B., Non linear finite elements for continua and structures, 2000, Wiley.
- Dhatt G., Touzot G. and Lefrancois E., Une présentation de la méthode des éléments finis, 2005, Hermes.
- Holzapfel G.A., Nonlinear solid mechanics, 2000, Wiley.
- Scott R., Introduction to Automated Modelling with Fenics, 2018, Computational Modelling Initiative LLC.
- Langtange, P. and Logg A., Solving PDEs in Python, 2017, Springer.
- Davide Bigoni Nonlinear Solid Mechanics Bifurcation Theory and Material Instability, 2012, Cambridge University Press.
- Wriggers, P., Nonlinear finite element method, 2008, Springer.
- Bonnet M., Frangi A., Rey C., The finite element method in solid mechanics, 2014, McGraw Hill.

Resources available to students. Annals.
Scientific knowledge developed in the unit.

- Ability to develop numerical code based on the finite element method to solve a linear and nonlinear elasticity problem in static or dynamic using the python language and the FEniCS library
- Non-linear elasticity, explicit and implicit methods for structural dynamics, numerical study of bifurcation and stability in the quasi-static framework.
- Introduction to revision management systems (git), Introduction to visualization and meshing tools, Use of large linear and nonlinear equation system solvers

Skills developed in the unit.

- Group work within the proposed project.
- Report and presentation.

Hourly volumes in and out of the classroom.
Total Attendance Hours: 30 hrs (integrated lectures and discussion sessions): Personal Work 30 hrs.

Evaluation.
The evaluation is based on a written report lasting 3 hours and a report associated with a mini-defence.

Teacher. Mr D. Duhamel, Mr C. Maurini

Introduction to homogenization in continuous media mechanics

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
The behaviour of materials can be modelled in two complementary ways: the phenomenological approach and the change of scale. The phenomenological approach consists in experimentally identifying behaviour laws at the scale of a representative volume element of the material, whereas the change of scale techniques propose to calculate estimates of the behaviour of the material from the behaviour of its constituents and their volume fractions. The purpose of this course is to introduce the basic concepts and techniques necessary to achieve, through change of scale, a homogenization of a linear elastic heterogeneous material.

Content of the Teaching Unit.

- Introduction of different scales of observation in heterogeneous solids. Notion of Representative Elementary Volume E (RVE).
- Homogeneous boundary conditions in strain or stress. Tensors of elasticity and flexibility of the VER.
- Voigt and Reuss terminals. Case of the unidirectional composite.
- Appropriate methods for low concentrations of inclusions. Overview of consistent methods at to and the Mori-Tanaka model.
- Case of media with a periodic structure.

Prerequisites. It is necessary to master the linear elastic modelling of deformable solids

Bibliographical references.

- Hashin Z., Analysis of composite materials, a survey. J. Appl. Mech., 50, 481-505 (1983) ;
- Sanchez-Hubert J., Sanchez-Palencia E., Introduction aux méthodes asymptotiques et à l'homogénéisation, Masson, Paris, 1992;
- Sab K., On the homogenization and simulation of random materials. Eur. J. Mech. A/Solids, 11 (5), 585-607. 1992 ;
- Nemat-Nasser S., Hori M., Micromechanics: Overall Properties of Heterogeneous Materials, North-Holland, 1993 ;
- KozlovS.M. OlenikO.,ZhikovV.,HomogenizationofDifferentialOperators,SpringerVerlag,1994;
- Sab K., Homogenized properties of heterogeneous elastic materials: definition and limits. Proceedings of the "change of scale" days. 7 and 8 June 2000. Nantes. LCPC. 2000 ;
- Bornert M., Bretheau T., Gilormini P. (Eds), Homogenisation en mécanique des matériaux, Hermes, Paris, 2001.

Resources available to students. Annals.

Scientific knowledge developed in the unit.

- Homogenization of elastic materials.

Skills developed in the unit.

- Practice of linear elasticity Modelling.
- Application and comparison of homogenization methods.
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Hourly volumes in and out of the classroom.
Total Attendance Hours: 30 hrs (integrated lectures and discussion sessions): Personal work 30 hrs.

Evaluation.
The evaluation is based on a written report lasting 3 hours.

Teacher. Mr K. Sab

Modelling and Simulation

Updated 01/03/2020

SCIENCES SORBONNE UNIVERSITÉ

Calculation code practice and applications II

Level CMI5 - **Semester** S9 - **Credits** 6 ECTS - **Code** MU5MES08 - Master's degree in Mechanics

Pedagogical presentation.
In this EU the advanced concepts of nonlinear solid mechanics introduced in the different courses of the common core of the Master of Solid Mechanics are illustrated with concrete numerical calculations. The numerical applications are based on the use of industrial code (Abaqus) and open libraries for finite elements (FEniCS).

Content of the Teaching Unit.

- Introduction to ABAQUS: Static and dynamic study, bending of beams, plates, static and linear dynamics.
- Multiphysical couplings: piezoelectric structures, anisotropic materials.
- Non-linear behaviour: plasticity with strain hardening (isotropic and kinematic), numerical algorithms.
- Linear fracture mechanics: numerical calculations of the energy restitution rate, singularities at the crack tip.
- Non-linear contact: Hertz contact with comparison of analytical formula, Behaviour of a rubber tube subjected to crushing.
- Linear buckling analysis of cylindrical shells.
- Explicit dynamics.
- Periodic homogenization.

Prerequisite. Mathematics, basic numerics. Mechanics of continuous media. Linear elasticity. Slender structures. Introduction to non-linear calculations of finite element structures.

Bibliographical references.
Those of the support UEs (MMC, Material Behaviour, Homogenisation).

Scientific skills developed in the unit.

- Solution of complex linear elasticity problems
- Introduction to numerical methods for fracture, plasticity, homogenization and contact
- Introduction to multi-physical couplings and active structures
- Introduction to non-linear problem solving

Skills developed in the unit.

- Advanced mastery of an industrial calculation code.
- Numerical solution of non-linear problems of structural calculations.
- Rigorous programming in compliance with the specifications.

Hourly volumes in and out of class. 8 h class + 52 h work, 60 h work out of class.

Evaluation. The evaluation is based on a 4-hour machine examination (case study).

Teacher. Mr A. Fernandes, Mrs S. Dartois

Updated 01/03/2020

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Damage

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES05 - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
The objectives of this teaching are:

- to provide the theoretical basis for the damage mechanics of quasi-fragile materials, in particular concerning the formulation of macroscopic behavioural laws coupling elasticity and damage.
- to study the problem of the initiation and evolution of damage in a numerical framework in order to address the poorly-positioned nature of local damage models and then to propose an opening towards several regularization techniques and links to brittle fracture models.

Content of the Teaching Unit.
After a brief introduction on the microscopic origin of damage as a process that changes the macroscopic properties of materials, the sessions of this course will be dedicated to :

- the formulation of the law of elastic-damageable behaviour in the context of irreversible thermodynamic processes (generalized standard materials) ;
- the introduction of the notion of damage criterion (threshold surface), of associated thermodynamic force (energy restitution rate) and of damage evolution law ;
- the simple implementation of an isotropic damage model in a finite element calculation code (FEniCS) ;
- the study of the malpositioning of local damage models (mesh dependence) and a presentation of different regulation techniques (non-local models) ;
- numerical implementation of `gradient damage models (phase-field) for the simulation of crack propagation in brittle materials;

Prerequisite. Mechanics of continuous media. Thermodynamics, numerical calculation (finite element method).

Bibliographical references.

- Lemaitre, J., Chaboche, J. L., Benallal, A., & Desmorat, R. (2009). Mechanics of solid materials - 3rd edition. Dunod.
- Pijaudier-Cabot G., Mazars J. (2001). Damage models for concrete. in Handbook of Materials Behavior. Vol. II, Lemaitre J. (ed.), Academic Press
- Marigo,J.J., Maurini, C.,& Pham, K.(2016). An overview of the modelling of fracture by gradient damage models. Meccanica, 51(12), 3107-3128.

Resources available to students. Course materials, Annals.

Scientific knowledge developed in the unit.

- Damage Modelling.
- Calculation of damaged structures.
- Crack propagation.

Skills developed in the unit.

- Implementation of a damage law in a calculation code.
- Respect of procedures during code development.

Hourly volumes in and out of the classroom.
Total Attendance Hours: 30 hrs (lectures and discussion sessions): Personal Work 30 hrs.

Evaluation.
The evaluation is based on a written report lasting 3 hours.

Teacher. Mr D. Kondo & Mr J. Bleyer

Fatigue

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
The engineer's mastery of mechanical design problems requires knowledge and understanding of all possible modes of failure. This course focuses on fatigue failure modes that may occur in structures subjected to time-varying stresses. At the end of the Teaching Unit, the students: (i) know the basic concepts of fatigue and damage accumulation in materials and structures under cyclic and possibly random loading; (ii) know the main criteria used in the industrial environment; (iii) be able to deduce the service life of a structure under cyclic loading; (iv) be able to explain the causes of failures observed in service.

Content of the Teaching Unit.

- *Physical phenomena.* Introduction of the problem from a practical case: axle-wheel-rail. Highlighting the phenomenon of fatigue. Wöhler curves. Distinction between low and high cycle fatigue. Physical mechanisms of fatigue (plasticity, cracking, distinction between initiation and propagation). *Cyclic loads and adaptation theorems.* Classification of cyclic behaviour in elasto-plasticity (adaptation, accommodation, ratchet). Long time convergence theorems. Adaptation theorems (static and kinematic). Extensions out of perfect plasticity.
- *Fatigue criterion.* Unlimited endurance Fatigue criterion with a large number of cycles, in uniaxial (Gerber parabola, Goodman's right) and multiaxial loading (including criteria of Sine, Crossland, Dang Van).
- *Fatigue criterion.* Limited endurance. Random loads Laws of limited endurance. Fatigue life at low number of cycles (Manson-Coffin's law, energy criterion). Miner accumulation rules. Stress-Strength method. Rainflow type counting.

Prerequisites. Mechanics of continuous media. Notions of plasticity.

Bibliographical references.

- Constantinescu, A., K. Dang Van, and M. H. Maitournam. ”A unified approach for cycle fatigue based on shakedown concepts.” Fatigue & fracture of engineering materials & structures 26.6 (2003) : 561-568.
- Bertolino, G., et al. ”A multiscale approach of fatigue and shakedown for notched structures.” Theoretical and Applied Fracture Mechanics 48.2 (2007) : 140-151.
- Peigney, Michael. ”Shakedown theorems and asymptotic behaviour of solids in non-smooth mechanics.” European Journal of Mechanics-A/Solids 29.5 (2010) : 784-793.
- Peigney, Michael. ”Shakedown of elastic-perfectly plastic materials with temperature-dependent elastic moduli.” Journal of the Mechanics and Physics of Solids 71 (2014) : 112-131.
- Papadopoulos, Ioannis V., et al. ”A comparative study of multiaxial high-cycle fatigue criteria for metals.” International Journal of Fatigue 19.3 (1997) : 219-235.
- Papadopoulos, Ioannis V. (editor) Multiaxial fatigue limit criterion of metals. Springer Vienna, 1999.

Resources available to students. Annals.

Scientific knowledge developed in the unit.

- Knowledge of the main criteria for fatigue.
- Aggregation rules.

Skills developed in the unit.

- Fatigue sizing of simple structures using the criteria seen in progress.
- Compare forecast results with test results. Critical analysis.

Hourly volumes in and out of the classroom.
Total Attendance Hours: 30 hrs (lectures and discussion sessions): Personal Work 30 hrs.

Evaluation.
The evaluation is based on a written report lasting 3 hours.

Teacher. Mr M. Peigney

Updated 01/03/2020

Durability of materials and structures

Updated 01/03/2020

SCIENCES SORBONNE UNIVERSITÉ

Elasticity and strength of heterogeneous materials

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Master's degree in mechanics**

Pedagogical presentation.
The course is aimed at students who are already familiar with the problem of changing scales.
It focuses on scale-change methods in the context of the non-linear behaviour of heterogeneous materials.

Content of the Teaching Unit.
After establishing the link between effective elasticity and deformation localization, the Eshelby problems of equivalent inclusion and inhomogeneity are introduced, from which the classical homogenization schemes (Mori-Tanaka, self-coherent) are presented.

Returning then to the notion of polarization in the perspective of constructing bounds, we introduce the Hashin-Shtrikman variational approach.

Non-linear homogenization is addressed by introducing the incremental and secant methods illustrated on the criterion of porous media rupture. This question is taken up again within the framework of Gurson's model.

Keywords : Location. Eshelby's problems. Eshelby homogenisation schemes. Hashin-Shtrikman terminals. Secant methods. Gurson's criterion.

Prerequisites: CMI4 Continuous Media Mechanics course. Methods of scale change.

Bibliographical references.

- Willis J.R. Bounds and self-consistent estimates for the overall moduli of anisotropic composites. J. Mech. Phys. Solids 25, 185-202, 1977.
- Ponte Castaneda P., Willis J.R. The effect of spatial distribution on the effective behavior of composite materials and cracked media. J. Mech. Phys. Solids, 43, 1919-1951, 1995.
- Bornert M., Bretheau T., Gilormini P. (Eds), Homogenization in Materials Mechanics, Hermes, Paris, 2001.
- Dormieux L., Kondo D., Ulm F.-J. Microporomechanics, Wiley, 2006.

Resources available to students. Books cited in the library and online articles.

Scientific knowledge developed in the unit.
- Non-linear homogenization methods.

Skills developed in the unit.
- Be able to implement the methods on simple cases.

Hourly volumes in and out of the classroom.
Total attendance: 24 hours of integrated lectures and discussion sessions. Personal work 30 hrs.

Evaluation. Written exam of 2 or 3 hours.

Teacher. Mr. L. Sleepy

Multi-scale approaches to metal plasticity

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
Metallic materials are widely used in industrial structural components in transportation and energy. The characteristics of their elastoplastic behaviour, such as strain-hardening and anisotropy, are largely the result of their crystalline nature and microstructure. The objectives of the course are, on the one hand, to recall the usual laws of elastoplastic behaviour and their use to predict plastic instabilities that are precursors of fracture, and, on the other hand, to formulate the laws of behaviour of single crystals in large anisotropic elastoplastic transformations characterising the deformation of the grains of the microstructure. The links between these two scales are finally addressed by the study of the polycrystal.

Content of the Teaching Unit.
Behavioural laws and elastoplastic instabilities. The reminders on the formulation of the time-independent elastoplastic laws (load surface, strain-hardening) are followed by the formulation of the problem at the speed limits and the introduction of the criterion of loss of uniqueness due to Hill for the prediction in particular of the modes of stressing prior to failure. The conditions for the formation of deformation localization bands, such as shear bands, are established following the Rice method. They coincide with the loss of ellipticity of the set of partial differential equations of the problem. They are used to predict the occurrence and orientation of elastoplastic localization bands. The course is also extended by the study of viscoplastic instabilities modes typical of static and dynamic ageing of metal alloys (Piobert-Lüders and Portevin-Le Chatelier bands). These instabilities are manifested by the propagation of localization bands whose thickness depends on the grain size.
Law of behaviour of the mechanical single crystal in finished transformations. The metallic single crystal deforms by sliding dislocations according to systems dictated by crystallography. Knowledge of this deformation mechanism enabled Jean Mandel to formulate the only law of behaviour in large elastoplastic deformations without ambiguity on the rotation of the microstructure in relation to matter. This theory is presented based on the multiplicative decomposition of the gradient of the transformation into elastic and plastic parts. It applies to shaping problems but also to the turbine blades of high pressure aircraft engine turbines. The identification of the parameters of the law from uniaxial mechanical tests is illustrated. Finally, the concept of dislocation density tensor is introduced to translate the heterogeneities of the deformationsS that develop in the grains of polycrystals.
Case studies by speakers from EDF R&D. Examples of the use of multi-scale behaviour laws for various metal alloys (steels and superalloys in particular) are given for applications in reactors and cooling systems of nuclear power plants. The importance of plasticity, crystallography, localization and fracture phenomena is highlighted.

Prerequisite. Mechanics of continuous media. Laws of elastoplastic behaviour.

Resources available to students. Handouts of course notes, transparencies presented.

Bibliographical references.

- J. Besson, G. Cailletaud, J.-L. Chaboche, S. Forest, M. Blétry, Springer, 2010: Non linear mechanics of materials. Series: Solid Mechanics and its Applications, Vol. 167, doi:10.1007/978-90-481-3356-7
- S. Forest, K. Ammar, B. Appolaire, N. Cordero and A. Gaubert, *Micromorphic approach to crystal plasticity and phase transformation*. In Plasticity and beyond, edited by J. Schroeder and K. Hackl, CISM International Centre for Mechanical Sciences 550, Courses and lectures, Springer, pp. 131-198, 2014.
- M. Mazière and S. Forest, *Strain gradient plasticity Modelling and finite element simulation of Lüders band formation and propagation,* Continuum Mechanics and Thermodynamics, vol. 27, pp. 83-104, 2015. doi:10.1007/s00161-013-0331-8

Scientific skills developed in the unit.
- Understanding the phenomenology and physics of plastic deformation of metals.
- Acquisition of criteria for instabilities and location of deformation in structures.

Skills developed in the unit.
- Familiarisation with the law of elastoplastic behaviour of single crystals in finished transformations used in industry and research.
- Application of the models in industrial cases.

Hourly volumes in and out of the classroom. The module consists of 8 sessions of 3 hours each.
Evaluation. The evaluation is based on a 3-hour review (case study).
Teacher. Mr. S. Forest, Mr. M. Mazière and Mr. F. Latourte.

Design and optimization of composite structures

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES09 -
Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
The objective of this course is to introduce the formulation of the different classes of finite dimensional optimization problems with applications to structural analysis, as well as the learning and practice of analytical and numerical solving methods (applications in DISCUSSION SESSIONS and LAB on examples of mechanics, structural optimization).

Content of the Teaching Unit.

- Introduction to optimization: various types of optimization problems, notions of objective function, constraints.
- Linear problems in finite dimensions :
  - simplex method; duality ;
  - application examples: limit analysis for bar systems (physical meaning of the dual problem), cost minimization of transmission and distribution networks.
- Non-linear problems in finite dimension without constraints :
  - existence, uniqueness, convexity (optimality conditions of order 1 and 2) ;
  - associated numerical methods (gradient, conjugate gradient, Newton) ;
  - examples of application: study of equilibrium and stability; identification of behavioural laws.
- Non-linear problems in finite dimension with constraints :
  - case of equality type constraints: Lagrange multipliers (optimality conditions of order 1 and 2) ;
  - case of inequality type constraints: Karush-Kuhn-Tucker conditions (of order 1 and 2 optimality) ;
  - associated numerical methods: projection, penalty and barriers
  - application examples: equilibrium and stability studies; examples of structural optimization.
- Applications in LAB and numerical project: practice of optimization algorithms (gradient and conjugate gradient, Newton, quasi-Newton, genetic algorithm) and solving optimization problems in solid and structural mechanics (project topics proposed to students).

Prerequisites. Mathematics: Linear algebra - Calculation of functions of several variables. Programming, scientific calculation

Bibliographical references.

- Pablo Pedregal, Introduction to Optimization, Springer, 2000
- David G. Luenberger, Linear and Nonlinear Programming, Addison-Wesley, 1973
- Gilbert Strang, Introduction to Applied Mathematics, Wellesley-Cambridge Press, 1986
- Raphael Haftka & Zafer Gürdal, Elements of Structural Optimization, Springer, 1991

Resources available to students. Course materials, corrected annals.

Scientific knowledge developed in the unit.

- Formulations of an optimization problem under constraints.
- Associated methods of resolution

Skills developed in the unit.

- Practice of optimization algorithms
- Application to problems of composite structures.

Hourly volumes in and out of the classroom.
Total classroom hours: 30 hours of classes and integrated tutorials. Expected personal work: 30 - 50 hrs. in a project
Evaluation. The evaluation is based on a written report and a project note.
Teacher. Mrs. A. Vincenti

Structural stability

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
The objective is to master the theoretical and numerical concepts associated with structural stability calculations. This includes the static and dynamic stability of equilibria (buckling, Hopf bifurcation) but also more advanced concepts such as material instabilities or the dynamic stability of periodic states (period doubling, Neimark-Sacker bifurcation) through the Floquet theory. These different problems will be treated with the help of concrete model examples that cover a large part of the instabilities encountered in engineering.

Content of the Teaching Unit.
Dynamical Systems Theory

- Stability and bifurcations
- Steady-state stability: buckling, fluttering and other cases
- Static approach
- Dynamic approach

Stability of periodic states

- Floquet Theory
- Dynamic instabilities and bifurcations.
- Applications to structures.

Prerequisite. Mathematics, basic numerical calculation. Know how to solve a problem with eigenvalues. Balance, stability, vibration in CMI3. Slim structures. Introduction to non-linear calculations of finite element structures.

Resources available to students.
Handouts of course notes, transparencies presented.

Bibliographical references.

- Strogatz, S. H., "Nonlinear Dynamics and Chaos: with applications to physics, biology, chemistry, and engineering", CRS Press, 2018.
- Lazarus A. Maurini C., Neukirch S., "Stability of Discretized Nonlinear Elastic Systems", in Extremely Deformable Structures, Springer Vienna, CISM Courses and Lectures, 562, 1-53, 2015.
- Païdoussis M.P., Price S.J., de Langre E., "Fluid-Structure Interactions: cross-flow-induced instabilities", Cambridge University Press, 2011.

Scientific skills developed in the unit.

- Theories associated with the course (buckling, bifurcations ...).

Skills developed in the unit.

- Recognize how to model and numerically process a stability problem in structural mechanics.

Hourly volumes in and out of the classroom.
The module consists of 4 sessions of 2 hrs, 14 hrs of Lab (3 hrs).

Evaluation. The evaluation is based on a 2-hour review (case study).

Teacher. Mr. A. Lazarus

SCIENCES
SORBONNE
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Multi-Scale Analysis
for materials and structures

Updated 01/03/2020

SCIENCES
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Nuclear Severe Accident Issues

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES18 - Master's degree in Mechanics

Pedagogical presentation.
The issue of nuclear safety is a crucial question in energy policy debates and sometimes seems to be either reserved for experts or reduced to an opposition of values.

The aim of this module is to give students the fundamentals of reasoning and construction of nuclear safety (particularly in France), then to teach them to apply them during the analysis of the most notable severe nuclear accidents and finally to exercise their critical thinking skills. Students are invited to carry out their own analysis of a nuclear accident to conclude and validate the module.

In concrete terms, this unit enables students to gain a pragmatic understanding of the issues associated with a severe nuclear accident and the relevant questions it raises. To this end, the module will integrate some basic notions in nuclear safety (health aspects, defence in depth, design, operation) by insisting on their own logic. Then reasoning and critical thinking will be tested through the successive analysis of the accidents of Three Miles Island, Chernobyl and Fukushima.

This module is essentially participatory, with students being regularly asked to put themselves in the shoes of the designer, operator, etc. to define their strategy.

At the end of the module, each student applies his or her knowledge and critical thinking skills in a case study.

Content of the Teaching Unit.

- The particularity of nuclear power: the health aspects.
- The concepts, principles and logic of reactor design and operation.
- The safety approach including feedback and key players.
- Analysis of the accidents at Three Miles Island, Chernobyl and Fukushima.
- Personal analysis of an accidental situation.

Prerequisite. The training does not require any particular pre-requisite as it aims to enable everyone to be able to exercise their critical thinking skills with regard to nuclear safety issues within a few hours.

Resources available to students.
Articles and technical reports distributed to students.

Bibliographical references.

Scientific skills developed in the unit.

Skills developed in the unit.

- Pragmatic understanding of the issues associated with a severe nuclear accident and the relevant questions it raises.
- Development of critical thinking skills in this type of event.

Hourly volumes in and out of the classroom.
The module consists of 6 sessions of 3 hours each, including the final evaluation. 20 hours of personal work.

Evaluation. The evaluation is based on a 3-hour review (case study).

Teacher. Manager from the nuclear industry (EdF). Stakeholder who may change.

Updated 01/03/2020

Physics and operation of Pressurized Water Reactors.

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES21 - Mechanical Master's **degree**

Pedagogical presentation.
By the end of this unit, students will be familiar with the main elements of the fuel cycle and the essential points related to the operation of pressurized light water reactors. They will have had to reflect on the concept of safety, waste management and the overall economics of this type of reactor.

Content of the Teaching Unit.

- Fuel - its evolution in PWRs
- The fuel cycle
- Loading and environment of components in service in PWRs
- Primary Chemistry
- Loss of coolant accidents
- Notions of safety
- Radioactive waste
- Fast neutron dies
- R&D for GEN IV
- Nuclear Economy 3

Prerequisite: None.

Bibliographical references.

Resources available to students. General documents and reports.

Scientific knowledge developed in the unit.

- Operation of a Pressurized Water Reactor.

Skills developed in the unit.

- Analyze technical documents.
- Write and present LAB RCs.

Hourly volumes in and out of the classroom.
Attendance total: conference cycle (9 of 3 hours). Personal work 20:00 - 30:00.

Evaluation. The knowledge control and validation of the module are based on a mini-memory work (study and bibliographical synthesis) or micro-project work (design of simplified models), which can be carried out in pairs.

Teacher. Mr H. Grard

Updated 01/03/2020

Physics and operation of Pressurized Water Reactors.

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES21 - Mechanical Master's **degree**

Pedagogical presentation.

By the end of this unit, students will be familiar with the main elements of the fuel cycle and the essential points related to the operation of pressurized light water reactors. They will have had to reflect on the concept of safety, waste management and the overall economics of this type of reactor.

Content of the Teaching Unit.

- Fuel - its evolution in PWRs
- The fuel cycle
- Loading and environment of components in service in PWRs
- Primary Chemistry
- Loss of coolant accidents
- Notions of safety
- Radioactive waste
- Fast neutron dies
- R&D for GEN IV
- Nuclear Economy 3

Prerequisite: None.

Bibliographical references.

Resources available to students. General documents and reports.

Scientific knowledge developed in the unit.

- Operation of a Pressurized Water Reactor.

Skills developed in the unit.

- Analyse technical documents.
- Write and present LAB RCs.

Hourly volumes in and out of the classroom.

Attendance total: conference cycle (9 of 3 hours). Personal work 20h – 30h.

Evaluation. The knowledge control and validation of the module are based on a mini-memory work (study and bibliographical synthesis) or micro-project work (design of simplified models), which can be carried out in pairs.

Teacher. Mr H. Grard

Uncertainty engineering in mechanics.

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - Master's degree in mechanics

Pedagogical presentation.
The consideration of uncertainties in mechanical and industrial problems is becoming essential in today's engineering. Indeed, it allows to reduce the design costs related to the over-dimensioning of structures, and brings a more realistic Modelling of systems.

The objective of the module is to introduce students to probabilistic approaches in engineering, by presenting the main tools for random modelling, and the main numerical methods for quantifying and propagating uncertainties.

Content of the Teaching Unit.
The course is divided into 4 blocks of 3 sessions.

1. Random modelling, statistical inference, Monte-Carlo method.
2. Reliability analysis, reduction of variance.
3. Uncertainty propagation, sensitivity analysis.
4. Model reduction.

Each of the four blocks is cut out in lectures, application exercises and practical work on the machine with the OpenTURNS software.

- A final session is devoted to the intervention of one or more industrial partners.

Prerequisite: None.

Bibliographical references. A bibliography is provided to students.

Resources available to students. The course slides and topics for practical work are available on the course web page. Access to the OpenTURNS software.

Scientific knowledge developed in the unit.
- Probabilistic approaches in engineering. Main random Modelling tools.
- Main associated numerical methods.

Skills developed in the unit.
- Propose an adequate probabilistic model to represent a database.
- Select and implement relevant numerical methods.

Hourly volumes in and out of the classroom.
Total attendance: 24 hours of integrated courses and practical work. Personal work 20 h - 30 h.

Evaluation. Written exam of 2 or 3 hours (50%) and Lab report (50%).

Teacher. Mr J. Reygnier, Mrs V. Galland Ehrlacher, École des Ponts et Chaussées.

Multi-scale approaches to metal plasticity

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
Metallic materials are widely used in industrial structural components in transportation and energy. The characteristics of their elastoplastic behaviour, such as strain-hardening and anisotropy, are largely the result of their crystalline nature and microstructure. The objectives of the course are, on the one hand, to recall the usual laws of elastoplastic behaviour and their use to predict plastic instabilities that are precursors of fracture, and, on the other hand, to formulate the laws of behaviour of single crystals in large anisotropic elastoplastic transformations characterising the deformation of the grains of the microstructure. The links between these two scales are finally addressed by the study of the polycrystal.

Content of the Teaching Unit.
Behavioural laws and elastoplastic instabilities. The reminders on the formulation of the time-independent elastoplastic laws (load surface, strain-hardening) are followed by the formulation of the problem at the speed limits and the introduction of the criterion of loss of uniqueness due to Hill for the prediction in particular of the modes of stressing prior to failure. The conditions for the formation of deformation localization bands, such as shear bands, are established following the Rice method. They coincide with the loss of ellipticity of the set of partial differential equations of the problem. They are used to predict the occurrence and orientation of elastoplastic localization bands. The course is also extended by the study of viscoplastic instabilities modes typical of static and dynamic ageing of metal alloys (Piobert-Lüders and Portevin-Le Chatelier bands). These instabilities are manifested by the propagation of localization bands whose thickness depends on the grain size.
Law of behaviour of the mechanical single crystal in finished transformations. The metallic single crystal deforms by sliding dislocations according to systems dictated by crystallography. Knowledge of this deformation mechanism enabled Jean Mandel to formulate the only law of behaviour in large elastoplastic deformations without ambiguity on the rotation of the microstructure in relation to matter. This theory is presented based on the multiplicative decomposition of the gradient of the transformation into elastic and plastic parts. It applies to shaping problems but also to the turbine blades of high pressure aircraft engine turbines. The identification of the parameters of the law from uniaxial mechanical tests is illustrated. Finally, the concept of dislocation density tensor is introduced to translate the heterogeneities of the deformationsS that develop in the grains of polycrystals.
Case studies by speakers from EDF R&D. Examples of the use of multi-scale behaviour laws for various metal alloys (steels and superalloys in particular) are given for applications in reactors and cooling systems of nuclear power plants. The importance of plasticity, crystallography, localization and fracture phenomena is highlighted.
Prerequisite. Mechanics of continuous media. Laws of elastoplastic behaviour.
Resources available to students. Handouts of course notes, transparencies presented.
Bibliographical references.

- J. Besson, G. Cailletaud, J.-L. Chaboche, S. Forest, M. Blétry, Springer, 2010: Non linear mechanics of materials. Series: Solid Mechanics and its Applications, Vol. 167, doi:10.1007/978-90-481-3356-7
- S. Forest, K. Ammar, B. Appolaire, N. Cordero and A. Gaubert, *Micromorphic approach to crystal plasticity and phase transformation*. In Plasticity and beyond, edited by J. Schroeder and K. Hackl, CISM International Centre for Mechanical Sciences 550, Courses and lectures, Springer, pp. 131-198, 2014.
- M. Mazière and S. Forest, *Strain gradient plasticity Modelling and finite element simulation of Lüders band formation and propagation,* Continuum Mechanics and Thermodynamics, vol. 27, pp. 83-104, 2015. doi:10.1007/s00161-013-0331-8

Scientific skills developed in the unit.
- Understanding the phenomenology and physics of plastic deformation of metals.
- Acquisition of criteria for instabilities and location of deformation in structures.

Skills developed in the unit.
- Familiarisation with the law of elastoplastic behaviour of single crystals in finished transformations used in industry and research.
- Application of the models in industrial cases.

Hourly volumes in and out of the classroom. The module consists of 8 sessions of 3 hours each.
Evaluation. The evaluation is based on a 3-hour review (case study).
Teacher. Mr S. Forest, Mr M. Mazière and Mr F. Latourte.

Concrete durability

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
The objective of this course is to provide students with an overview of the issues faced by civil engineering managers. The point of view adopted is that of a nuclear operator, all the speakers being EDF R&D employees involved in the management of nuclear civil engineering structures, and to a lesser extent other civil engineering structures such as dams. The student who follows this course will thus have at its end a culture on the properties of concrete, its physical and mechanical properties, its durability against external attacks or against endogenous reactions. In addition, the methods used to diagnose these pathologies on structures and to measure quantities of interest, as well as the methods of dimensioning of structures and re-calculation according to the evolution of different pathologies, are discussed.

Content of the Teaching Unit.
Concrete formulation. As an introduction to the course, the basics of concrete formulation are presented. The main properties of the different constituents of concrete are discussed, as well as the chemistry of hydration, and the methods for characterizing fresh and hardened concrete.
Construction of reinforced and prestressed concrete structures, external attacks. This two-part session first presents the main concepts to be retained concerning the construction of reinforced and prestressed concrete structures. In a second step, the main chemical reactions of external origin causing concrete degradation are presented (carbonation, leaching, chloride attack, corrosion, freeze-thaw).
Auscultation of GC works. An introduction to the main techniques for the examination of GC structures is provided. Methods for monitoring in the context of containment are detailed.
Drying, shrinkage and creep of concrete, at the material level. The physical origins of these phenomena are discussed in order to show the complexity of the phenomena occurring in concrete structures, and the difficulties involved in being able to simulate the evolution of the state of a concrete structure.
Visit of EDF Lab Les Renardières: VeRCoRs model and GC laboratory. In order to concretely show an example of a GC structure for nuclear (Vercors) and the means of characterising concrete (GC lab), a visit to the Les Renardières site is made (open to all Master's students).
Consequence of deferred deformations on the structures. This session shows how deferred deformation phenomena affect the durability of civil engineering structures.
From design to evaluation of behaviour over time in an aggressive environment. After targeted reminders on the behaviour of concrete, reinforced concrete and prestressed concrete, the main assumptions used for the design of GC structures are recalled, with a focus on plates and massive areas. Several examples are then presented.
Degradation of concretes by endogenous reactions. Bases on the alkali-aggregate reaction and the internal sulfatic reaction are introduced. An example of the impact of these endogenous reactions on an EDF structure is then presented.

Prerequisite. General knowledge of materials mechanics.
Resources available to students.
Numerous scientific documents provided to students related to each field.
Scientific skills developed in the unit.
- Modelling of the different chemical attacks on concrete.

Skills developed in the unit.
- General knowledge of the behaviour of reinforced and prestressed concrete structures.
- Overview of studies conducted by facility managers to optimize the service life of structures.

Hourly volumes in and out of the classroom. The module consists of 8 sessions of 3 hours each.
Evaluation. The evaluation is based on a 3-hour review (case study).
Teacher. ENPC Teacher

SCIENCES SORBONNE UNIVERSITÉ

Modelling and simulation of equipment and structures and application to seismic analysis

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
This module is part of the 2nd year Master's Degree: "Durability of Materials and Structures", whose aim is to address "the problems of strengthening industrial facilities" (in this case nuclear reactors, dams, etc.). More precisely, it is a question of mastering the numerical modelling used to justify the safety and operation over the lifetime of the structures and in particular according to changes in seismic reference systems. The objectives of the module are: acquisition of the necessary scientific elements, development of models of the mechanical behaviour of equipment and structures, application to their static and earthquake resistance, mastery of the associated calculation tool.

Content of the Teaching Unit.
Session 0: Reminders of solid and structural dynamics.
Session 1: General introduction of the module. Student expectations. Theoretical reminders on finite elements: simulation in linear elasticity. Numerical analysis reminders: existence and uniqueness, finite elements. Solving algorithms. Film " SMART ", 17min.
Session 2: Introduction to structural design software. Getting to grips with the Salomé platform: Structure of a design and calculation software; Types of calculations and post-processing that can be performed; assumptions, errors. Exercise in DISCUSSION SESSIONS: Getting to grips with the Salomé CAD+Mesh software. Presentation of the projects and choice by the students of their project.
Session 3: Simulation in linear statics, models of structures (beams, plates, discrete). Ex. in DISCUSSION SESSIONS: linear statics on a simple case (perforated plate) with the *Salomé_Méca* tool.
Session 4: Dynamic structure analysis: analysis methods in *Salome_Meca*. Exercises in DISCUSSION SESSIONS: linear dynamics on a simple case with the *Salomé_Méca* tool.
Session 5: Exercises in DISCUSSION SESSIONS: Linear calculation of the structure or equipment chosen. Follow-up of the students' work and assistance.
Session 6: Introduction to non-linear computation (material and geometric non-linearities), stability and limit analysis. Exercises in DISCUSSION SESSIONS: Non-linear calculus on the students' project. Follow-up of the students' work: assistance.
Session 7: DISCUSSION SESSIONS exercises: Non-linear calculation on the students' project. Follow-up of the students' work: assistance.
Session 8: Introductory presentation on seismic analysis: issues and modelling of seismic loading for equipment and structures; principles and methods in sizing and reassessment of existing facilities. Synthetic reminders of structural dynamics for seismic analysis: oscillator response spectra, seismic design rules; behaviour of buildings under earthquake.
Session 9: Seismic behaviour of pressurized water nuclear reactor components: vessel and core, reservoirs, with fluid-structure interaction; free surface tilting; behavioural non-linearities and buckling, following pressures. Seismic strength of piping lines in a building. DISCUSSION SESSIONS exercises: simplified Housner and Westergaard approaches; floor-equipment interaction.
Session 10: Introduction of seismic analysis on the students' project: choice of the problem, data collection and hypotheses, choice of methods, complements of modelling with *Salomé_Méca*. Presentation and implementation in Salomé_Méca of seismic analysis methods: modal analysis, spectral modal analysis, non-linear transient analysis, treatment of uncertainties.
Session 11: Follow-up of the work on the students' project: attendance.
Session 12: Follow-up of the work on the students' project: attendance.
Session 13: Follow-up of the work on the students' project: attendance.
Session 14: Evaluation of students' work: oral presentation of hypotheses and numerical study results, accompanied by a support file.

Some theoretical reminders will be given to make the module accessible to students who have not followed certain prerequisite modules.

Prerequisite. Structural Mechanics Course, Continuous Media Mechanics Course, Structural Dynamics Course (Advanced Dynamics, Structural Dynamics, Industrial Dynamics and Stability), Numerical Mechanics Course, Plasticity and Fracture Computation, Advanced Structural Computation.

Updated 01/03/2020

Resources available to students

- A handout (outline of the course); the transparencies presented during the session; support sheets for the Tutorials. Access on https://educnet.enpc.fr/course.
- Access to the website: www.code-aster.org, with training, theoretical and application documents.

Bibliographical references.

- Batoz J.-L., Dhatt G., Finite element Modelling of structures. Vol.1-2-3, Hermes, 1990.
- Clough R.-W., Penzien J., Dynamics of Structures. Computers & Structures Inc., Berkeley, 2003.
- Dhatt G., Touzot G. A presentation of the finite element method - 2nd edition. Maloine, 1984.
- Ern A. Finite Elements Checklist, Dunod, 2005.
- Pecker A. Dynamics of Structures, Dynamics of Structures. ENPC course handouts, 2009.
- Betbeder-Matibet J. Earthquake engineering. Éditions Hermès-Sciences-Lavoisier, Paris, 2003.
- Voldoire F., Bamberger Y. Mechanics of structures: initiation, in-depth study, applications. Presses des Ponts éditeurs, 2008. Available at the School's library.

Scientific skills developed in the unit.

- To master the models and methods dedicated to the fine analysis in statics and dynamics of the behaviour of structures and equipment within their environment, integrating couplings (fluid-structure...) and non-linear behaviours (both material and kinematics).

Skills developed in the unit.

- Implement these models in numerical simulation by finite elements with *Code_Aster* within the simulation platform *Salomé_Méca*.
- Critical analysis of the calculation results by confronting the complexity of the real problems in the case of earthquake resistance of structures and equipment of power generation facilities.

Hourly volumes in and out of the classroom.

The module consists of 15 sessions of 3 hours, including the final evaluation. Class sessions: 17 hours (8 presentations). Small Class Tutorials: 25 hours. Final evaluation: last session of 3 hours.

Evaluation. The evaluation is based on a 3-hour review (case study).

Teacher. Mr A. Pecker

SCIENCES SORBONNE UNIVERSITÉ

Elasticity and strength of heterogeneous materials

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES12 - Mechanical Master's **degree**

Pedagogical presentation.
The course is aimed at students who are already familiar with the problem of changing scales. It focuses on scale-change methods in the context of the non-linear behaviour of heterogeneous materials.

Content of the Teaching Unit.
After establishing the link between effective elasticity and deformation localization, the Eshelby problems of equivalent inclusion and inhomogeneity are introduced, from which the classical homogenization schemes (Mori-Tanaka, self-coherent) are presented.

Returning then to the notion of polarization in the perspective of constructing bounds, we introduce the Hashin-Shtrikman variational approach.

Non-linear homogenization is addressed by introducing the incremental and secant methods illustrated on the criterion of porous media rupture. This question is taken up again within the framework of Gurson's model.

Keywords: Location. Eshelby's problems. Eshelby homogenisation schemes. Hashin-Shtrikman terminals. Secant methods. Gurson's criterion.

Prerequisites: Continuing Mechanics course. Methods of changing scales.

Bibliographical references.

- Willis J.R. Bounds and self-consistent estimates for the overall moduli of anisotropic composites. J. Mech. Phys. Solids 25, 185-202, 1977.
- Ponte Castaneda P., Willis J.R. The effect of spatial distribution on the effective behavior of composite materials and cracked media. J. Mech. Phys. Solids, 43, 1919-1951, 1995.
- Bornert M., Bretheau T., Gilormini P. (Eds), Homogenization in Materials Mechanics, Hermes, Paris, 2001.
- Dormieux L., Kondo D., Ulm F.-J. Microporomechanics, Wiley, 2006.

Resources available to students. Books cited in the library and online articles.

Scientific knowledge developed in the unit.
- Non-linear homogenization methods.

Skills developed in the unit.
- Be able to implement the methods on simple cases.

Hourly volumes in and out of the classroom.
Total attendance: 24 hours of integrated lectures and discussion sessions. Personal work 30 hrs.

Evaluation. Written exam of 2 or 3 hours.

Teacher. M. L. Dormieux, École des Ponts et Chaussées

SCIENCES SORBONNE UNIVERSITÉ

Homogenisation in fracture calculation: from material to work

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES13 - Master's degree in Mechanics

Pedagogical presentation.
The ambition of the course "Applied Poromechanics" is mainly to train students to model the behaviour and transport laws in porous media in the framework of a multi-scale strategy. The latter is based on the writing of physical laws at the small scale in order to better understand their consequences at the scale of the structural material. This approach has largely demonstrated its effectiveness in the context of its application to materials for industry, mechanical engineering and civil engineering.

Content of the Teaching Unit.

- Average in porous media. Notion of Representative Elemental Volume. Introduction to the writing of different averages used, in the analysis of porous media, to characterize equivalent homogeneous behaviours and field equations at the macroscopic scale.
- Multi-scale approach to transport laws. Definition of diffusion and advection transport laws at the microstructure scale. Stokes/Darcy crossing. Estimates of homogenized diffusion coefficients and permeability for random microstructures. Thermal analogues.
- Saturated poroelastic behaviour. State equations of linear poroelasticity of saturated porous media (direct and energetic approaches). Notions of effective stress (Biot, Terzaghi). Drained and undrained evolutions. Estimates of homogenized poroelastic parameters. Notions of quadratic means.
- Unsaturated poroelastic behaviour. State equations of linear poroelasticity of unsaturated porous media. Bishop's effective stress. Consideration of surface stresses. Capillary pressure laws pc(Sr) and pc(HR). Equivalent formulation and associated effective stress.
- Physico-chemical couplings and modelling. Analysis of coupled phenomena in porous media: behaviour of a porous medium subjected to the freezing of interstitial water, analysis and modelling of the alkali-reaction phenomenon in concretes, poroelastic behaviour of partially saturated argillite.

Prerequisites. Mechanics of continuous media.

Bibliographical references.

- Microporomechanics. L. Dormieux, D. Kondo, F-J Ulm. ISBN: 978-0-470-03188-9, 2006, 344 p.
- Study of the macroscopic behaviour of a deformable saturated porous medium. J-L. Auriault, E. Sanchez-Palencia. J. de Mécanique, 16(4): 575-603, 1977.
- Mechanics of saturated and unsaturated porous media. X. Chateau, L. Dormieux. International Journal for Numerical and Analytical Methods in Geomechanics 26(8):831 - 844 · July 2002.
- Heterogeneous and composite materials. A. Zaoui. Course of the École Polytehnique, 1996.

Scientific knowledge developed in the unit.

- Multi-scale modelling of diffusive and advective transport in porous media
- Formulation of linear poroelasticity under saturated and unsaturated conditions
- Methods for estimating the various poromechanical parameters introduced
- Management of coupled physico-chemical phenomena in a micromechanical strategy

Skills developed in the unit.

- Mastering and promoting the multi-scale approach for the analysis and understanding of coupled behaviours in porous media. Writing of advective and diffusive transport in porous media.
- Estimation of macroscopic transport properties (diffusion, permeability).
- Formulation of the saturated and unsaturated poroelastic behaviour of porous media.
- Consideration of physico-chemical couplings. Estimation of macro poroelastic parameters.

Hourly volumes in and out of the classroom. Total classroom hours: 18 hours divided into 12 hours of classes and 6 hours of discussion sessions. Personal work 30-40 hours.
Evaluation. The evaluation is based on a 2-hour exam.
Teacher. M. L. Dormieux, École des Ponts et Chaussées.

Homogenisation in fracture calculation: from material to work

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES14- Master's degree in Mechanics

Pedagogical presentation.

The objective of the course is to illustrate the methods of construction of structural models with the case of anisotropic laminated plates.
These models are relevant for applications such as laminated composite materials (carbon fibre/glass), glued laminated or cross laminated timber structures (Cross Laminated Timber).
The approach is based on the construction of an approximation of the 3D field in the form of separate variables (plane/off-plane) and application of a relevant variational principle to obtain the equations of the structural model. The specificity of this course is that static approaches are preferred whereas the majority of approaches in the literature are kinematic.

Content of the Teaching Unit.

- Anisotropic elasticity reminders and variational principles.
- Equivalent single-layer plate models. Kinematic and then static construction of the homogeneous thick plate model (membrane forces, bending moments and shear forces). Changeover to thin plate model (Kirchhoff connection). Extension to laminated plate models.
- Multi-layer plate models. Static construction of the family of Multi-Particle Models for Multi-Layer Materials and application.

Prerequisites. Mechanics of continuous media.

Bibliographical references.

- Baroud R, Sab K, Caron J, et al. International Journal of Solids and Structures A statically compatible layerwise stress model for the analysis of multilayered plates. *International Journal of Solids and Structures* 2016;96:11–24.
- Hadj-Ahmed R, Forêt G, Ehrlacher A, et al. Stress analysis in adhesive joints with a multiparticle model of multilayered materials (M4). *International Journal of Adhesion* 2001;21:297–307.
- Hencky H. On the consideration of shear distortion in plane plates. *Engineer archive* 1947;16:72-6.
- Lebée A, Sab K. On the Generalization of Reissner Plate Theory to Laminated Plates, Part I: Theory. *Journal of Elasticity* 2017;126:39–66.
- Naciri T, Ehrlacher A, Chabot A. Interlaminar stress analysis with a new Multiparticle modelization of Multilayered Materials (M4). *Composites Science and Technology* 1998;58:337–43.
- Philippe M-H, Naciri T, Ehrlacher A. A tri-particle model of sandwich panels. *Composites Science and Technology* 1999;59:1195–206.
- Reissner E. On the theory of bending of elastic plates. *J Math Phys* 1944;23:184–91.

Skills developed in the unit.

- Methods of dimension reduction within linearized elasticity.

Hourly volumes in and out of the classroom.

Total attendance hours: 18 hours divided into 12 hours of class and 6 hours of discussion sessions. Personal work 30-40 hours.

Evaluation. The evaluation is based on a 3-hour exam accompanied by homework (2-3).

Teacher. Mr K. Sab, École des Ponts et Chaussées.

SCIENCES SORBONNE UNIVERSITÉ

Image and mechanics

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** MUSME16 - Mechanical Master's **degree**

Pedagogical presentation.
Imaging techniques have changed our daily lives considerably in recent years. They have also induced a profound change in the experimental mechanics of materials and structures. This course aims to provide some keys to apprehend the mechanical behaviour of materials with these new tools. It describes the main surface and volume imaging techniques used in experimental mechanics, as well as the exploitation of the information contained in the images produced using image analysis methods. These concern on the one hand the characterization of microstructures, with a view to using this information in the framework of analytical or numerical methods of change of scale, addressed in other courses of the master's programme. On the other hand, it is possible to extract from the images qualitative and quantitative indications on the evolution of materials under stress. The associated techniques, known as field measurement techniques, provide a quantity of information infinitely richer than conventional point measurements, which can be compared with numerical simulation tools, with a view to identifying and validating models of the behaviour of materials and structures.

Content of the Teaching Unit.

- Main image acquisition tools (macro- and optical microscopy, scanning and transmission electron microscopy, analytical techniques, X-ray microtomography, diffraction techniques).
- Image processing: image coding, filtering, segmentation, introduction to mathematical morphology, statistical analysis.
- Imaging and scaling: links with theoretical models and microstructural computation
- Measurement of kinematic fields. Main "photomechanical" techniques. Correlation of digital images. Nanoindentation. Dans Whenever possible, the lectures will be illustrated by demonstrations on devices available at Navier or in nearby laboratories.

Prerequisites: Continuous Media Mechanics course.

Bibliographical references.

- G. Wastiaux, La microscopie optique, Tec&Doc, 1994.
- C. Colliex, Electron Microscopy, Puf, 1996.
- F. Brisset (Ed.), Scanning Electron Microscopy and Microanalysis, EDP Sciences, 2008.
- J. Baruchel et al., X-Ray tomography in material science, Hermes, 2000.
- J.F. Chermant and Coster, Précis d'analyse d'images, CNRS editions.
- J. Serra, Image Analysis and Mathematical morphology, Academic press, 1982.
- S. Torquato, Random heterogeneous materials, Springer, 2001.
- Handbook on Experimental mechanics, Kobayashi, Wiley, 1993.
- M. Sutton, J.J. Orteu and H. Schreier, Image correlation for shape, motion and deformation measurements, Springer 2009.
- M. Grédiac and F. Hild, Field measurements and identification, Hermes Sciences, 2011.

Resources available to students. Books cited in the library and online articles.

Scientific knowledge developed in the unit.

- Operation of optical and scanning microscopes.
- Image analysis methods in the context of heterogeneous solid mechanics.
- Introduction to mathematical morphology.

Skills developed in the unit.

- Developing an image processing algorithm to derive deformation maps.

Hourly volumes in and out of the classroom.
Total Attendance Hours: 24 hours of integrated lectures and discussion sessions. Expected personal work: 8:00 - 30:00 p.m.

Evaluation. The evaluation of the module will be done in the form of a mini-project including a bibliographical part and an experimental or digital implementation.

Teacher. Mr M. Bornert, Mr S. Brisard, École des Ponts et Chaussées.

Updated 01/03/2020

Damage

Level CMI5 - **Semester** S9 - **Credits** 3 ECTS - **Code** MU5MES05 - Master's degree in Mechanics / Solid Mechanics. Materials and structures.

Pedagogical presentation.
The objectives of this teaching are:

- to provide the theoretical basis for the damage mechanics of quasi-fragile materials, in particular concerning the formulation of macroscopic behavioural laws coupling elasticity and damage.
- to study the problem of the initiation and evolution of damage in a numerical framework in order to address the poorly-positioned nature of local damage models and then to propose an opening towards several regularization techniques and links to brittle fracture models.

Content of the Teaching Unit.
After a brief introduction on the microscopic origin of damage as a process that changes the macroscopic properties of materials, the sessions of this course will be dedicated to :

- the formulation of the law of elastic-damageable behaviour in the context of irreversible thermodynamic processes (generalized standard materials) ;
- the introduction of the notion of damage criterion (threshold surface), of associated thermodynamic force (energy restitution rate) and of damage evolution law ;
- the simple implementation of an isotropic damage model in a finite element calculation code (FEniCS) ;
- the study of the malpositioning of local damage models (mesh dependence) and a presentation of different regulation techniques (non-local models) ;
- numerical implementation of `gradient damage models (phase-field) for the simulation of crack propagation in brittle materials;

Prerequisite. Mechanics of continuous media. Thermodynamics, numerical calculation (finite element method).

Bibliographical references.

- Lemaitre, J., Chaboche, J. L., Benallal, A., & Desmorat, R. (2009). Mechanics of solid materials - 3rd edition. Dunod.
- Pijaudier-Cabot G., Mazars J. (2001). Damage models for concrete. in Handbook of Materials Behavior. Vol. II, Lemaitre J. (ed.), Academic Press
- Marigo,J.J., Maurini, C.,& Pham, K.(2016). An overview of the modelling of fracture by gradient damage models. Meccanica, 51(12), 3107-3128.

Resources available to students. Course materials, Annals.

Scientific knowledge developed in the unit.

- Damage Modelling.
- Calculation of damaged structures.
- Crack propagation.

Skills developed in the unit.

- Implementation of a damage law in a calculation code.
- Respect of procedures during code development.

Hourly volumes in and out of the classroom.
Total Attendance Hours: 30 hrs (lectures and discussion sessions): Personal Work 30 hrs.

Evaluation.
The evaluation is based on a written report lasting 3 hours.

Teacher. Mr D. Kondo & Mr J. Bleyer

SCIENCES SORBONNE UNIVERSITÉ

Multi-scale approaches to metal plasticity

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
Metallic materials are widely used in industrial structural components in transportation and energy. The characteristics of their elastoplastic behaviour, such as strain-hardening and anisotropy, are largely the result of their crystalline nature and microstructure. The objectives of the course are, on the one hand, to recall the usual laws of elastoplastic behaviour and their use to predict plastic instabilities that are precursors of fracture, and, on the other hand, to formulate the laws of behaviour of single crystals in large anisotropic elastoplastic transformations characterising the deformation of the grains of the microstructure. The links between these two scales are finally addressed by the study of the polycrystal.

Content of the Teaching Unit.
Behavioural laws and elastoplastic instabilities. The reminders on the formulation of the time-independent elastoplastic laws (load surface, strain-hardening) are followed by the formulation of the problem at the speed limits and the introduction of the criterion of loss of uniqueness due to Hill for the prediction in particular of the modes of stressing prior to failure. The conditions for the formation of deformation localization bands, such as shear bands, are established following the Rice method. They coincide with the loss of ellipticity of the set of partial differential equations of the problem. They are used to predict the occurrence and orientation of elastoplastic localization bands. The course is also extended by the study of viscoplastic instabilities modes typical of static and dynamic ageing of metal alloys (Piobert-Lüders and Portevin-Le Chatelier bands). These instabilities are manifested by the propagation of localization bands whose thickness depends on the grain size.
Law of behaviour of the mechanical single crystal in finished transformations. The metallic single crystal deforms by sliding dislocations according to systems dictated by crystallography. Knowledge of this deformation mechanism enabled Jean Mandel to formulate the only law of behaviour in large elastoplastic deformations without ambiguity on the rotation of the microstructure in relation to matter. This theory is presented based on the multiplicative decomposition of the gradient of the transformation into elastic and plastic parts. It applies to shaping problems but also to the turbine blades of high pressure aircraft engine turbines. The identification of the parameters of the law from uniaxial mechanical tests is illustrated. Finally, the concept of dislocation density tensor is introduced to translate the heterogeneities of the deformationsS that develop in the grains of polycrystals.
Case studies by speakers from EDF R&D. Examples of the use of multi-scale behaviour laws for various metal alloys (steels and superalloys in particular) are given for applications in reactors and cooling systems of nuclear power plants. The importance of plasticity, crystallography, localization and fracture phenomena is highlighted.

Prerequisite. Mechanics of continuous media. Laws of elastoplastic behaviour.
Resources available to students. Handouts of course notes, transparencies presented.
Bibliographical references.

- J. Besson, G. Cailletaud, J.-L. Chaboche, S. Forest, M. Blétry, Springer, 2010: Non linear mechanics of materials. Series: Solid Mechanics and its Applications, Vol. 167, doi:10.1007/978-90-481-3356-7
- S. Forest, K. Ammar, B. Appolaire, N. Cordero and A. Gaubert, *Micromorphic approach to crystal plasticity and phase transformation*. In Plasticity and beyond, edited by J. Schroeder and K. Hackl, CISM International Centre for Mechanical Sciences 550, Courses and lectures, Springer, pp. 131-198, 2014.
- M. Mazière and S. Forest, *Strain gradient plasticity Modelling and finite element simulation of Lüders band formation and propagation,* Continuum Mechanics and Thermodynamics, vol. 27, pp. 83-104, 2015. doi:10.1007/s00161-013-0331-8

Scientific skills developed in the unit.
- Understanding the phenomenology and physics of plastic deformation of metals.
- Acquisition of criteria for instabilities and location of deformation in structures.

Skills developed in the unit.
- Familiarisation with the law of elastoplastic behaviour of single crystals in finished transformations used in industry and research.
- Application of the models in industrial cases.

Hourly volumes in and out of the classroom. The module consists of 8 sessions of 3 hours each.
Evaluation. The evaluation is based on a 3-hour review (case study).
Teacher. Mr. S. Forest, Mr. M. Mazière and Mr. F. Latourte.

Concrete durability

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.

The objective of this course is to provide students with an overview of the issues faced by civil engineering managers. The point of view adopted is that of a nuclear operator, all the speakers being EDF R&D employees involved in the management of nuclear civil engineering structures, and to a lesser extent other civil engineering structures such as dams. The student who follows this course will thus have at its end a culture on the properties of concrete, its physical and mechanical properties, its durability against external attacks or against endogenous reactions. In addition, the methods used to diagnose these pathologies on structures and to measure quantities of interest, as well as the methods of dimensioning of structures and re-calculation according to the evolution of different pathologies, are discussed.

Content of the Teaching Unit.

Concrete formulation. As an introduction to the course, the basics of concrete formulation are presented. The main properties of the different constituents of concrete are discussed, as well as the chemistry of hydration, and the methods for characterizing fresh and hardened concrete.

Construction of reinforced and prestressed concrete structures, external attacks. This two-part session first presents the main concepts to be retained concerning the construction of reinforced and prestressed concrete structures. In a second step, the main chemical reactions of external origin causing concrete degradation are presented (carbonation, leaching, chloride attack, corrosion, freeze-thaw).

Auscultation of GC works. An introduction to the main techniques for the examination of GC structures is provided. Methods for monitoring in the context of containment are detailed.

Drying, shrinkage and creep of concrete, at the material level. The physical origins of these phenomena are discussed in order to show the complexity of the phenomena occurring in concrete structures, and the difficulties involved in being able to simulate the evolution of the state of a concrete structure.

Visit of EDF Lab Les Renardières: VeRCoRs model and GC laboratory. In order to concretely show an example of a GC structure for nuclear (Vercors) and the means of characterising concrete (GC lab), a visit to the Les Renardières site is made (open to all Master's students).

Consequence of deferred deformations on the structures. This session shows how deferred deformation phenomena affect the durability of civil engineering structures.

From design to evaluation of behaviour over time in an aggressive environment. After targeted reminders on the behaviour of concrete, reinforced concrete and prestressed concrete, the main assumptions used for the design of GC structures are recalled, with a focus on plates and massive areas. Several examples are then presented.

Degradation of concretes by endogenous reactions. Bases on the alkali-aggregate reaction and the internal sulfatic reaction are introduced. An example of the impact of these endogenous reactions on an EDF structure is then presented.

Prerequisite. General knowledge of materials mechanics.

Resources available to students.

Numerous scientific documents provided to students related to each field.

Scientific skills developed in the unit.

- Modelling of the different chemical attacks on concrete.

Skills developed in the unit.

- General knowledge of the behaviour of reinforced and prestressed concrete structures.
- Overview of studies conducted by facility managers to optimize the service life of structures.

Hourly volumes in and out of the classroom. The module consists of 8 sessions of 3 hours each.

Evaluation. The evaluation is based on a 3-hour review (case study).

Teacher. ENPC Teacher

Homogenisation in fracture calculation: from material to work

Level CMI5 - **Semester** S2 - **Credits** 3 ECTS - **Code** - Master's degree in Mechanics

Pedagogical presentation.
The objective of this course is to present and then implement the method of homogenization of periodic media in fracture calculation. Emphasis will be placed on the determination in simple cases (multilayer models, linearly reinforced composites, etc.) of the macroscopic failure criterion of such heterogeneous materials, with a view to its application to the design of structures.

Content of the Teaching Unit.

- General presentation of the theory of fracture calculus: static approach from the inside and kinematic approach from the outside.
- Homogenization method in fracture calculation: initial problem and associated homogeneous problem; notion of auxiliary fracture calculation problem; macroscopic strength criterion and corresponding support function; strength anisotropy.
- Explicit formulation of the macroscopic failure criterion for materials with simple structure: multilayer media, linearly reinforced materials (fibre composites, reinforced floors), porous media, joint masonry. Consideration of interfaces.
- Implementation of static and kinematic approaches of computation at break for the resolution of the associated homogeneous problem. Relevance and efficiency of the homogenization method for the dimensioning of structures.
- Simplified formulation of the criterion in the case of high-strength thin linear reinforced composites. Opening towards a multiphase Modelling of the resistance of these composite media. Notion of interaction resistance.

Prerequisites. Mechanics of continuous media.

Bibliographical references.

- P. SUQUET (1985). Elements of homogenization for inelastic solid mechanics. *CISM Lecture Notes*, n°272, « Homogenization Techniques for Composite Media », Springer-Verlag, pp. 193-278.
- P. de BUHAN (1986) A *fundamental approach to the fracture design of reinforced soil structures*. State thesis, University of Paris VI.
- P. de BUHAN, R. MANGIAVACCHI, R. NOVA, G. PELLIGRINI, J. SALENCON (1989). Yield design of reinforced earth walls by a homogenization method. *Géotechnique*, 39, n°2; pp. 189-201.
- P. de BUHAN, A. TALIERCIO (1991). A homogenization approach to the yield strength of composite materials, *Eur. J. Mech. A/Solids*, 10(2), pp129-150.
- P. de BUHAN, L. DORMIEUX (1996). On the validity of the effective stress concept for assessing the strength of saturated porous materials : a homogenization approach. *J. Mech. Phys. Solids*, Vol. 44, N°10, pp. 1649-1667.
- P. de BUHAN, G. de FELICE (1997). A homogenization approach to the ultimate strength of brick masonry. *J. Mech. Phys. Solids*, Vol. 45, N°7, pp. 1085-1104.
- S. MAGHOUS, P. de BUHAN, A. BEKAERT (1998). Failure design of jointed rock structures by means of a homogenization approach. *Mech. Cohes.-Frict. Mater.*, 3, pp. 207-208.
- B. JELLALI, M. BOUASSIDA, P. de BUHAN (2005). A homogenization method for estimating the bearing capacity of soils reinforced by columns. *Int. J. Num. Anal. Meth. Geomech.*, Vol 29, pp. 1-16.
- Q. THAI SON, G. HASSEN, P. de BUHAN (2009). A multiphase approach to the stability analysis of reinforced earth structures accounting for a soil-strip failure condition. *Computers and Geotechnics*, 36, pp. 454-462.

Resources available to students

Scientific knowledge developed in the unit.

- Homogenization in the context of computation at break.

Skills developed in the unit.

- Periodic homogenization in a practical case.
- Fracture calculation applied to simple structures. Application to floors.

Hourly volumes in and out of the classroom.
Total in-class hours: 21 hours divided into 7 sessions of 3 hours (lectures and discussion sessions). Personal work 30 hrs.

Evaluation.
The assessment is based on a review of 2 papers.

Teacher. Mr P. de Buhan

Updated 01/03/2020

Methods for identifying model parameters

Level CMI5 - **Semester** S3 - **Credits** 3 ECTS - **Master's degree in mechanics**

Pedagogical presentation.
The behaviour of materials is described by models involving parameters that are not always accessible through direct measurements. Thus, it is often necessary to use specific identification methods.

Content of the Teaching Unit.
- The identification of parameters in the more general framework of inverse problems. Numerous examples in various fields. Reminder of the mathematical concepts used in this course.
- The inverse linear inverse problem in finite dimension. Linear least squares, singular value decomposition and regularization techniques.
- Unconstrained optimization methods and optimality conditions in the differentiable and non-differentiable convex case. The conjugated function of Legendre-Fenchel. Different algorithms (descents, dual methods, ...).
- Optimization methods with constraints and the Lagrangian notion. Optimality conditions in the differentiable case, link between optimization and duality. Characterization and identification of parameters in the laws of material behaviour.
- Optimization methods with constraints in the non-differentiable convex case (Karush- Kuhn-Tucker). Algorithms (internal or external penalty methods, dual methods).
- Laws of behaviour: notions of thermodynamic potentials, dissipation potentials. Examples in dimension 1.

Prerequisites: Continuous Media Mechanics course and notions on the laws of non-linear behaviour.
Bibliographical references.

- ALLAIRE G., 2005, Analyse numérique et optimisation, Les Éditions de l'École polytechnique or ALLAIRE G., 2007, Numerical Analysis and Optimization, Oxford University Press.
- BERGOUNIOUX M., 2001, Optimisation and optimal control, Dunod.
- BUI H.D., 1993. Introduction to inverse problems in material mechanics. Collection of the Direction des Etudes et Recherches d'Electricité de France. Eyrolles.
- CHABOCHE J-L., BENALLAL A., DESMORAT R., 2009, Mécanique des matériaux solides, 3rd edition, Dunod.
- CHONG E.K.P., ZAK S.H., 2001. An Introduction to Optimization. Wiley.
- CULIOLI J. C., 1994, Introduction to optimization, Ellipses.
- GROETSCH C.W. ,1993. Inverse Problems in the Mathematical Sciences. Vieweg Mathematics for Scientists and Engineers.
- KIRSCH A., 1996. An Introduction to the Mathematical Theory of Inverse Problems. Springer

Resources available to students. Books cited in the library and online articles.

Scientific knowledge developed in the unit.
- Inverse methods for identifying behavioural law parameters.
- Optimization under constraints.
- Non-convex case.

Skills developed in the unit.
- Apply in simple cases the methods seen in progress.

Hourly volumes in and out of the classroom.
Total attendance: 24 hours of integrated lectures and discussion sessions. Personal work 20 h - 30 h.

Evaluation. Written exam of 2 or 3 hours.

Teacher. Mr. P. Argoul

Semester 10

Updated 01/03/2020

Deepening Project

Level CMI5 - **Semester** S10 - **Credits** 3 ECTS - **Code** MU5EEG04 - Master's **degree in** Mechanics

Pedagogical presentation.
This deepening project is complementary to the specialization and can take different forms. It can represent the follow-up of an optional unit of additional specialization in semester S9 to broaden the knowledge base or to enhance a bibliographical part of the internship that would have been significant, or be associated with a scientific production for example in the context of the internship (presentation in a scientific conference, submission of a publication). It can also valorise an important associative investment or translate the validation of a teaching in the form of a MOOC (for example, a shared teaching on the European Virtual Exchange platform of the Sorbonne University Alliance 4eu+ network of partner universities: Charles University of Prague (Czech Republic), Heidelberg (Germany) and Warsaw (Poland), Universities of Milan (Italy) and Copenhagen (Denmark)). This project is usually carried out on an individual basis.

Content of the Teaching Unit.
Depending on the form of the project

Prerequisite miminum. Knowledge acquired in all teaching units since CMI1.

Bibliographical references. Function of the project subject.

Resources available to students. Function of the project subject and its environment.

Scientific knowledge developed in the unit

- Function of the project subject.

Skills developed in the unit.

- Take a step back from his training path.
- Knowing how to manage a personal project with commitment, defending it with conviction.

Hourly volumes in and out of the classroom.
Expected personal work: about 30 - 40 hours (and often more).

Evaluation. Evaluation usually in the form of a note of the written report, oral defence and involvement.

Teacher. Y. Berthaud, H. Dumontet.

Graduation internship

Level CMI5 - **Semester** S10 - **Credits** 30 ECTS - **Code** MU5MES03 - **Mention** Master Mechanics

Pedagogical presentation.
This end-of-study internship takes place over 24 weeks at the end of the course. The objective is to enable the student to acquire an engineering attitude, in particular autonomy and the ability to work effectively in a team in the company, by relying on the knowledge acquired during the training and the skills developed in the simulation activities (projects, and previous internships). He consolidates the specialization and validates these acquired skills.

This internship can take place in France or abroad, in a company (generally in the R&D departments of large industrial groups) or research laboratory (provided that the student then has significant experience of an internship in a company). It leads to the writing of a report and a defence in French or English. The presentation is made in front of a mixed jury composed of members of the teaching team and external experts, including the supervisor in the case of an internship in a company.

Content of the Teaching Unit.
The course leaders validate the coherence of the subject, its adequacy with the speciality of the training, with the student's professional project and his/her academic results. This internship is the subject of an internship agreement signed by the company/laboratory, the university and the student.

Prerequisite miminum. All the knowledge and skills developed since the beginning of the course.

Resources available to students.
- List and description of previous internship topics. Internship offers.
- Validation procedures, drafting guidelines, internship agreements.
- Bibliographical resources according to the subject.

Scientific knowledge developed in the unit.
- Specific to each internship according to the subject area of the company / laboratory and the missions entrusted.

Skills developed in the unit.
- Knowing how to participate in teamwork, take initiatives, know how to situate oneself and acquire autonomy.
- Know how to apply one's knowledge and apply it to a new open subject.
- Be able to respect specifications and deadlines.
- Be Teacher for the quality of his work.
- Take a step back from his experience, gain confidence in professional integration.
- Know how to communicate about your work in writing and orally.

Hourly volumes in and out of the classroom. 24 weeks of full-time internship between March and the end of August.

Evaluation. Placement report (/35, about fifty pages excluding annexes), tutor evaluation (/30), oral defence (/35 , 25 minutes presentation, 25 minutes questions).

Teacher. Course managers, Mr. Y. Berthaud and Mrs H. Dumontet (LECTUREI officials).