RUHR-UNIVERSITÄT BOCHUM

RUB

FAKULTÄT FÜR
BAU- UND UMWELT-
INGENIEURWISSENSCHAFTEN

# Master‘s Program
# *Computational Engineering*

CompEng
Computational Engineering

# Module Handbook

## Curriculum
## Module description

# Introduction

The Module handbook provides detailed information regarding the course content and curriculum of the Master's Program 'Computational Engineering'.

1. Modularization (Modularisierungskonzept)
    - The course curriculum has a modular structure. It consists of compulsory modules, elective modules and optional modules.
    - Credit points (CP) according to the European Credit Transfer System (ECTS) are awarded for the successful completion of each module. One CP according to the ECTS corresponds to an average student workload of 30 hours. The number of credit points awarded for a certain module depends on the workload (see module description of the lecture for further details).
2. Curriculum (Studienplan)
    - The Master's program has a duration of 4 semesters. The compulsory courses in the first semester build a core set of skills in Numerical Mathematics, Computational Mechanics, Computer Science and other relevant courses. The specialization phase in the second and third semesters is flexible and allows students to focus on the different lines of Computational Engineering by choosing courses of their own choice from the course catalogue. In the fourth semester, students prepare their master's thesis in a research field that is relevant for computational engineering. In total, 120 CP according to the ECTS are required for the successful completion of the Master's program. The complete course catalogue is provided below.
3. Types of examinations (Prüfungsform) and examination regulations (Prüfungsordnung)
    - With the exception of the Master's thesis, examinations are module examinations, either graded or ungraded (see module descriptions for further details). They may be conducted in the form of a written examination, an oral examination, by working on tasks during the course, a project, a seminar paper, a report or a colloquium presentation. Please refer to the examination regulations (Prüfungsordnung) for further details.
4. Grading of the master's examinations
    - The overall grade (avg) of the master's examination arises as a weighted arithmetic mean (weighted with the CPs) of all graded module examinations with the exception of the optional modules. When calculating the overall grade, the grades for the compulsory modules with a factor of 1, the grades for the compulsory optional modules with a factor of 1.5, and the grade for the master's thesis with a factor of 2.0 are weighted in addition. Decimal values are to one decimal place.
5. Counseling (Beratung)
    - The CompEng Coordination Office is maintained by the Faculty of Civil and Environmental Engineering. Its members offer counseling on study related matters to students of the Master's program. In addition, the lecturers of the Master's program provide consultation hours, during which students may clarify questions concerning the respective course.

## Changes in the summer semester 2025

| Module number | Module Title | Module coordinator and lecturer(s) | Change |
|---|---|---|---|
| CE-WP04 | Nonlinear Finite Element Methods for Structures | Sauer | New title<br>Old Title: Advanced Finite Element Methods |
| CE-WP06 | Inelastic Finite Element Method for Structures | Sauer | 3CP -> 6 CP<br>New Module Title<br>Now offered in the winter semester |
| CE-WP09 | Numerical Simulation in Geotechnics and Tunneling | Wichtmann, Schmüdderich | Both parts will now be offered by the Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics (Prof. Wichtmann) |
| CE-WP29 | Uncertainty Quantifications in FE Analyses with Surrogate Modelling | Cao, Neu | New Module |
| CE-WP30 | Transient Finite Element and Finite Differences Methods | Sauer, Butt | New Module |
| CE-WP31 | Scientific C++ Programming (Basics) | Vogel | Now offered as an compulsory optional course. Old module number CE-W09 |
| CE-WP32 | Scientific C++ Programming (Advanced) | Vogel | Now offered as an compulsory optional course. Old module number CE-W10;<br>Offered in the summer semester 2025 during the semester, not as a block course. |
| CE-WP33 | Deep Learning for Engineers | Vogel | New Module |
| CE-WP34 | Advanced Discretization Methods | Vogel | New Module |
| CE-W06 | Advanced Constitutive Models for Geomaterials | Wichtmann, Schmüdderich | New content, previous components of the Chair of Structural Mechanics (Prof. Sauer) not included, now completely offered by the Chair of Soil Mechanics, Foundation Engineering and Environmental Geotechnics (Prof. Wichtmann),<br>3 CP -> 6CP |

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|---|---|---|---|
| CE-W07 | Project Management for Engineers | Cavara | is no longer offered |

# Curriculum

## Master's Program Computational Engineering

### Curriculum

| | | Code | Module Name | hours per week | CP | Semester |
|---|---|---|---|---|---|---|
| 1st & 2nd semester | **P** Compulsory Courses 39 CP | CE-P01 | Mathematical Aspects of Differential Equations and Numerical Mathematics | 4 | 6 | 1 |
| | | CE-P02 | Mechanical Modeling of Materials | 4 | 6 | 1 |
| | | CE-P03 | Computer-based Analysis of Steel Structures | 4 | 6 | 1 |
| | | CE-P04 | Scientific Programming | 4 | 6 | 1 |
| | | CE-P05 | Finite Element Methods in Linear Structural Mechanics | 4 | 6 | 1 |
| | | CE-P06 | Fluid Dynamics | 2 | 3 | 2 |
| | | CE-P07 | Continuum Mechanics | 4 | 6 | 2 |
| | | | **Subtotal CP: Compulsory Courses** | | 39 | |
| 1st, 2nd & 3rd semester | **WP** Compulsory Optional Courses 35 CP | CE-WP01 | Variational Calculus and Tensor Analysis | 3 | 5 | 1 |
| | | CE-WP31 | Scientific C++ Programming (Basics) | 2 | 3 | 1 |
| | | CE-WP02 | Optimization Aided Design - Reinforced Concrete | 4 | 6 | 2 |
| | | CE-WP03 | Adaptronics | 3 | 5 | 2 |
| | | CE-WP04 | Nonlinear Finite Element Methods for Structures | 4 | 6 | 2 |
| | | CE-WP05 | Computational Fluid Dynamics | 4 | 6 | 2 |
| | | CE-WP08 | Numerical Methods and Stochastics | 4 | 6 | 2 |
| | | CE-WP09 | Numerical Simulation in Geotechnics and Tunneling | 4 | 6 | 2 |
| | | CE-WP10 | Object-oriented Modeling and Implementation of Structural Analysis Software | 2 | 3 | 2 |
| | | CE-WP11 | Applied Computational Simulations of Structures | 4 | 6 | 2 |
| | | CE-WP12 | Computational Plasticity | 4 | 6 | 2 |
| | | CE-WP25 | High-Performance Computing on Multicore Processors | 4 | 6 | 2 |
| | | CE-WP28 | Machine Learning: Supervised Methods | 4 | 6 | 2 |
| | | CE-WP30 | Transient Finite Element and Finite Difference Methods | 4 | 6 | 2 |
| | | CE-WP32 | Scientific C++ Programming (Advanced) | 2 | 3 | 2 |
| | | CE-WP33 | Deep Learning for Engineers | 4 | 6 | 2 |
| | | CE-WP34 | Advanced Discretization Methods | 2 | 3 | 2 |
| | | CE-WP06 | Inelastic Finite Element Method for Structures | 3 | 6 | 3 |
| | | CE-WP13 | Advanced Control Methods for Adaptive Mechanical Systems | 4 | 6 | 3 |
| | | CE-WP14 | Computational Wind Engineering | 2 | 3 | 3 |
| | | CE-WP15 | Coupled Multiphysical Modeling and Simulations | 4 | 6 | 3 |
| | | CE-WP16 | Computational Modeling of Membranes and Shells | 4 | 6 | 3 |
| | | CE-WP17 | Numerical Methods for Conservation Laws | 4 | 6 | 3 |
| | | CE-WP19 | Computational Fracture Mechanics | 4 | 6 | 3 |
| | | CE-WP20 | Materials for Aerospace Applications | 4 | 6 | 3 |
| | | CE-WP21 | Quantum Computing | 4 | 6 | 3 |
| | | CE-WP26 | High-Performance Computing on Clusters | 4 | 6 | 3 |
| | | CE-WP29 | Uncertainty Quantification in FE Analyses with Surrogate Modeling | 4 | 6 | 3 |
| | | CE-WP24 | Case Study A | 2 | 3 | 2+3 |
| | | | **Minimum Subtotal CP: Compulsory optional courses** | | 35 | |
| 1st, 2nd & 3rd semester | **W** Optional Courses 16 LP | CE-W01 | Training of Competences (part 1) | 4 | 4 | 1 |
| | | CE-W02 | Training of Competences (part 2) | 4 | 4 | 2 |
| | | CE-W04 | Recent Advances in Numerical Modeling and Simulation | 2 | 2 | 2 |
| | | CE-W05 | Machine Learning: Evolutionary Algorithms | 4 | 6 | 2 |
| | | CE-W06 | Advanced Constitutive Models for Geomaterials | 2 | 6 | 2 |
| | | CE-W03 | Case Study B | 2 | 3 | 2+3 |
| | | | other relevant courses of the faculty or from engineering faculties of other universites | | | 1+2+3 |
| | | | **Minimum Subtotal CP: Optional Courses** | | 16 | |
| 4th Semester | **M** Master-Thesis | CE-M | Master Thesis | - | 30 | 4 |
| | | | **Subtotal CP: Master Thesis** | | 30 | |

| | | | |
|---|---|---|---|
| Subtotal CP: Compulsory Courses | | 39 | |
| Subtotal CP: Compulsory optional courses | | 35 | |
| Subtotal CP: Optional courses | | 16 | |
| Subtotal CP: Master Thesis | | 30 | |
| **Sum CP in total:** | | **120** | |

# Content

# Compulsory Courses
# CE-P01 - P07

## Mathematical Aspects of Differential Equations and Numerical Mathematics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-P01/MADENM | 6 CP | 180 h | $1^{st}$ Sem. | Winter term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Mathematical Aspects of Differential Equations and Numerical Mathematics | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**
No prior knowledge or preliminary modules. Basic calculus and experience with matrices.

**Learning goals / Competences**
The course will focus on the mathematical formulation of differential equations with applications to elastic theory and fluid mechanics. It gives an introduction to geometric linear algebra with emphasis on function spaces, coupled with the elementary aspects of partial differential equations. The students should learn to understand the mathematics side of the Finite Element Method (FEM) for elliptic PDE in low dimensions, appropriate Sobolev geometries, the FEM for Dirichlet and Neumann problems. For that reason, the basic principles in methods of error estimation are described to realize the understanding of fast and efficient solvers for the resulting matrix equations. As overall learning goal, the students should attain familiarity with modern methods and concepts for the numerical solution of complicated mathematical problems.
After successfully completing the module, the students

- should understand the mathematics side of the Finite Element Method for elliptic PDE in low dimensions, appropriate Sobolev geometries, the FEM for Dirichlet and Neumann problems,
- should attain familiarity with modern methods and concepts for the numerical solution of complicated mathematical problems.

**Content**
Linear algebra: Basic concepts and techniques for finite- and infinite-dimensional function spaces stressing the role of linear differential operators. Numerical algorithms for solving linear systems. The mathematics of the finite element method in the context of elliptic partial differential equations (model problems) in dimension two.

**Teaching methods / Language**
Lecture (2h / week), Exercises (2h / week) / English
Remark: Due to the mixed background of the students, the exercise sessions often amount to additional lectures.

**Mode of assessment**
Written examination (120 min, 100%)

**Requirement for the award of credit points**
Passed final module examination

**Module applicability** (in other study programs)
MSc. Computational Engineering

**Weight of the mark for the final score**
4 %

**Module coordinator and lecturer(s)**
Prof. Dr. G. Röhrle, Assistants

**Further information**

## Mechanical Modeling of Materials

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-P02/ MMoM | 6 CP | 180 h | $1^{st}$ Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Mechanical Modeling of Materials | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge in Mathematics and Mechanics (Statics, Dynamics and Strength of Materials)

**Learning goals / competences:**

The objective of this class is to present advanced issues of mechanics and the continuum-based modeling of materials starting with basic rheological models. The concepts introduced will be applied to numerous classes of materials. Basic constitutive formulations will be discussed numerically.

After successfully completing the module, the students

- should have a deep understanding of the theoretical basis of classical material models,
- should know how to derive constitutive equations from rheological models,
- should be able to implement a material model with a suitable algorithmic treatment in finite element software.

**Content**

Several advanced aspects regarding the modeling of the mechanical behavior of materials are addressed in this course. More precisely, the following topics will be covered:

- Basic concepts of continuum mechanics (introduction)
- Introduction to the rheology of materials
- Theoretical concepts of constitutive modeling
- Derivation of 1- and 3-dimensional models in the geometrically linearized setting for
    - Linear- and nonlinear elasticity
    - Damage
    - Visco-elasticity
    - Elasto-plasticity
- Aspects of parameter identification/adjustment
- Algorithmic implementation in the context of the finite element method and analysis of simple boundary and initial value problems

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Written examination (90 min, 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering

**Weight of the mark for the final score**

4 %

**Module coordinator and lecturer(s)**

Prof. Dr.-Ing. D. Balzani, Assistants

**Further information**

## Computer-based Analyses of Steel Structures

| **Module-No./Abbreviation** | **Credits** | **Workload** | **Term** | **Frequency** | **Duration** |
|---|---|---|---|---|---|
| CE-P03/CbASS | 6 CP | 180 h | $1^{st}$ Sem. | Winter term | 1 Semester |
| **Courses**<br>a) Basics of Analysis and Design, Numerical simulations in Steel Design, Fundamentals for computer-oriented Structural Analysis and Design assisted by Finite Element Analysis<br>b) Stability Behavior – Members and Plated Structural Elements<br>c) Structural Durability | | | **Contact hours**<br>4 SWS (60 h) | **Self-Study**<br>120 h | **Group Size:**<br>No Restrictions |

**Prerequisites**

Fundamental knowledge in mechanics and strength of materials

**Learning goals / competences:**

This course will introduce students to the fundamental structural and fatigue behavior of steel structures, numerical solution procedures and modeling details. The course aims to achieve a basic understanding of applied mechanics approaches to modeling member behavior in steel structure problems. The course is addressed to young engineers, who will face the necessity of numerical analysis and applied mechanics more often in their design practice.

The purpose of this course is to bridge the gap between applied mechanics and structural steel design using state-of-the-art tools. The students shall become familiar with computer-oriented analyses and assessment methods by using the example of steel constructions. The course will also convey to students the ability to use numerical tools and software packages for the solution of practical problems in engineering.

After successfully completing the module, the students

- have fundamental knowledge on structural and fatigue behavior of steel structures with the application of numerical procedures and modeling,
- should be familiarized with basic principles of design and computer-oriented procedures in assessing steel structures, their stability behavior and durability,
- will have gained experience in undertaking new concepts on their own and participate in in-class collaborative learning through the Inverted-classroom format,
- will have gained skills in working on a problem individually and in groups, presenting their findings in interactive presentations as well as assessing the findings of their peers.

**Content**

This course is introductory – by no means does it claim completeness in such dynamically developing fields as numerical analysis of slender steel structures and structural durability. The course intends to achieve a basic understanding of applied mechanics approaches to slender steel structure modeling and structural durability, which can serve as a foundation for the exploration of more advanced theories and analyses of different kind of structures.

*Basics of the Analysis, Design and Fundamentals for Computer-Based Calculations*

- Basic principles of structural design
- Beam theory and torsion
- Finite elements for beams and plates
- Software for analyses

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| *Stability Behavior of Slender Structures and Second Order Theory*<br>• Geometric non-linear design of structures - second order analysis<br>• Buckling of linear members and frames<br>• Lateral buckling and lateral torsional buckling<br>• Eigenvalues and –shapes<br>• Numerical methods for plate buckling<br>*Structural Durability*<br>• Fatigue<br>• Modern Concepts of Fatigue Strength Design<br>• Local Strain Concept<br>• Crack Propagation Concept |
| **Teaching methods / Language**<br>Lecture (2h / week), Exercises (2h / week) / English<br>The course is partially conducted in the Blended Learning and Inverted-Classroom formats. |
| **Mode of assessment**<br>Written examination (180 min, 100%) |
| **Requirement for the award of credit points**<br>Passed final module examination |
| **Module applicability**<br>MSc. Computational Engineering |
| **Weight of the mark for the final score**<br>4 % |
| **Module coordinator and lecturer(s)**<br>Deputy Professor Dr.-Ing. Rebekka Winkler, Assistants |
| **Further information** |

## Scientific Programming

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-P04, SE-O-10/SP | 6 CP | 180 h | 1st Sem. | Winter term | 1 Semester |
| **Course** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Scientific Programming | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**
No prior knowledge or preliminary modules.

**Learning goals / Competences:**
After successfully completing the module, the students
- have acquired the fundamental skills for the development of software solutions, including programming concepts and constructs, data structures and algorithms,
- are able to analyze problems with respect to their structure and requirements and are capable of designing and implementing suitable software code,
- can implement typical problems in scientific computing using the Python programming language and are able to quickly adapt the learned concepts to other programming languages.

**Content**
The lecture covers programming concepts such as
- procedural programming, including data types, statements and functions,
- object-oriented programming, including encapsulation, polymorphism and inheritance,
- generic programming.

Furthermore, fundamental data structures as well as efficient algorithms are presented, relevant software libraries are surveyed, and the organization of software projects is discussed.

In hands-on sessions, programming exercises are used to discuss and illustrate the presented content, employing the Python programming language for selected scientific applications.

**Teaching methods / Language**
Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**
Written examination (120 min, 100%)

**Requirement for the award of credit points**
Passed final module examination

**Module applicability**
MSc. Computational Engineering, MSc. Subsurface Engineering

**Weight of the mark for the final score**
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**Module coordinator and lecturer(s)**
Prof. Dr. A. Vogel, Assistants

**Further information**

## Finite Element Methods in Linear Structural Mechanics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-P05/ FEM-I | 6 CP | 180 h | 1st Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| FEM in Linear Structural Mechanics | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Basics in Mathematics, Mechanics and Structural Analysis (Bachelor level)

**Learning goals / Competences**

After successfully completing the module, the students

- have basic knowledge of the Finite Element Method (FEM),
- are able to transfer initial boundary value problems of structural mechanics into discretized calculation models based on FEM and thus to solve simple tasks of structural mechanics independently (e.g. calculation of truss structures, disc-like or volume structures),
- have advanced knowledge to understand the functionality of calculation programs based on FEM and to critically evaluate their results,
- are able to independently implement corresponding user-defined elements in FE programs and perform numerical analyses of beam and shell structures.

**Content**

The course covers the basic knowledge of linear FEM, which is based on the principle of virtual work. In particular, the following topics are taught in the course:

- Isoparametric finite elements for trusses, two-dimensional elements, beams, three-dimensional volume elements for application in statics and dynamics,
- consistent explanation of the fundamentals (basic equations, principle of variation),
- Numerical integration, assembly of the elements to a discretized structure and the solution of the static and dynamic structure equation,
- Discussion of stiffening effects ("locking") and their avoidance.

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Written examination (120 min, 100%) / Optional tasks to be solved at home and announced during the course, to get the bonus points for the exam.

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

4 %

**Module coordinator and lecturer(s)**

Prof. Dr. R. Sauer, Assistants

**Further information**

## Fluid Dynamics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-P06/FD | 3 CP | 90 h | $2^{nd}$ Sem. | Summer term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Fluid Dynamics | 2 SWS (30 h) | 60 h | No Restrictions |

**Prerequisites**

Mathematical Aspects of Differential Equations and Numerical Methods (CE-P01), Mechanical Modeling of Materials (CE-P02), Fluid Mechanics (Bachelor level)

**Learning goals / Competences**

The students shall acquire consolidated skills of the basic laws of hydraulics, potential theory, flow dynamics and turbulence theory. The students shall be enabled to assess and to solve technical problems related to flow dynamics in hydraulics and in aerodynamics.

After successfully completing the module, the students will be able to

- understand the broad scope of fluid dynamics and the thematic integration of computational fluid dynamics within,
- identify fluid dynamical mechanisms of observed flow phenomena and recognize the governing physical laws,
- choose and apply adequate engineering models to explore and formulate engineering solutions for real flows,
- solve fluid dynamical problems of acceptable complexity tailored to the student’s study status,
- validate and assess these solutions and the achieved results,
- acquire skills in numeracy, media literacy, and digital competence through the completion of supervised and supported self-studies and other activities.

**Content**

The technical basics of dynamic fluid flows are introduced, studied and recapitulated as well as related problems which are relevant for practical applications and solution procedures with an emphasis put on numerical and computational aspects.

The lectures and exercises contain the following topics:

- Short review of hydrostatics and dynamics of incompressible flows involving friction (conservation of mass, energy and momentum, Navier-Stokes equations)
- Boundary layer theory and introduction to non-isotropic turbulence
- Spectral analysis of turbulent boundary layer flows
- Flow over bluff bodies
- Gaseous transport in the urban environment
- Introduction to engineering applications for CFD method
- Considerations for CFD meshes and numerical domains
- Derivation of the Navier-Stokes equations
- Simulation types and turbulence modeling
- Boundary conditions for external flows
- Discretization methods, focusing on the finite volume method
- Solution algorithms, errors, validation, and verification

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| The students are guided in the exercises to working out assessment and solution strategies for related, typical technical problems in fluid dynamics |
| **Teaching methods / Language**<br>Lecture (2h / week), Exercises (2h / week) / English |
| **Mode of assessment**<br>Written examination (75 min) |
| **Requirement for the award of credit points**<br>Passed final module examination |
| **Module applicability**<br>MSc. Computational Engineering |
| **Weight of the mark for the final score**<br>2 % |
| **Module coordinator and lecturer(s)**<br>Prof. Dr.-Ing. R. Höffer, Assistants |

## Continuum Mechanics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-P07/CM | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Continuum Mechanics | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Mathematical Aspects of Differential Equations and Numerical Methods (CE-P01), Mechanical Modeling of Materials (CE-P02)

**Learning goals / Competences**

Extended knowledge in continuum-mechanical modeling and solution techniques as a prerequisite for computer-oriented structural analysis.

After successfully completing the module, the students

- will possess extended knowledge of continuum mechanics
- will be able to formulate problems of structural and material mechanics within the framework of continuum mechanics
- will have mastered solution techniques for mechanical problems as a prerequisite for computer-oriented analysis
- will be able to create mathematical models for engineering systems and processes
- will be able to interpret modeling results and revise models accordingly

**Content**

The course starts with an introduction to the advanced analytical techniques of linear elasticity theory, then moves on to the continuum-mechanical concepts of nonlinear elasticity and ends with the discussion of material instabilities and microstructures.

Numerous examples and applications will be given:

- Advanced Linear Elasticity
- Beltrami equation
- Navier equation
- Stress-functions
- Scalar- and vector potentials
- Galerkin-vector
- Love-function
- Solution of Papkovich - Neuber
- Nonlinear Deformation
- Strain tensor
- Polar descomposition
- Stress-tensors
- Equilibrium
- Strain-rates
- Nonlinear Elastic Materials
- Covariance and isotropy
- Hyperelastic materials
- Constrained materials
- Hypoelastic materials

| |
|---|
| • Objective rates<br>• Material stability<br>• Microstructures |
| **Teaching methods / Language**<br>Lecture (2h / week), Exercises (2h / week) / English |
| **Mode of assessment**<br>Written examination (120 min, 100%) |
| **Requirement for the award of credit points**<br>Passed final module examination |
| **Module applicability**<br>MSc. Computational Engineering |
| **Weight of the mark for the final score**<br>4 % |
| **Module coordinator and lecturer(s)**<br>Prof. Dr.-Ing. Johanna Waimann, Assistants |
| **Further information** |

# Compulsory Optional Courses
# CE-WP01 – WP34

## Variational Calculus and Tensor Analysis

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP01/VCTA | 5 CP | 150 h | 1st Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Variational Calculus and Tensor Analysis | | | 3 SWS (45 h) | 105 h | No Restrictions |

**Prerequisites**
Basic knowledge in Mathematics and Mechanics

**Learning goals / Competences**
The objective of this course is to introduce students to the fundamentals of vector and tensor algebra and its application to continuum mechanics. Moreover, the course will address basic aspects of variational methods in engineering.
After successfully completing the module, the students will be able

- to read, write and interpret tensor expression in index and abstract notation,
- to know and apply tools for formulating and manipulating the equations of continuum mechanics,
- to understand and solve variational problems in mechanics.

**Content**
Tensor Analysis:

- Vector and tensor notation and algebra
- Coordinates in Euclidean space, change of coordinates
- Differential calculus
- Scalar invariants and spectral analysis
- Isotropic functions

Variational Calculus:

- First variation
- Boundary conditions
- PDEs: Weak and strong form
- Constrained minimization problems, Lagrange multipliers
- Applications to continuum mechanics

**Teaching methods / Language**
Lecture (2h / week), Exercises (1h / week) / English

**Mode of assessment**
Written examination (90 min, 100%)

**Requirement for the award of credit points**
Passed final module examination

**Module applicability**
MSc. Computational Engineering

**Weight of the mark for the final score**
5 %

**Module coordinator and lecturer(s)**
Prof. Dr.-Ing. Johanna Waimann, Dr.-Ing. U. Hoppe

**Further information**

## Optimization Aided Design - Reinforced Concrete

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP02/OAD-RC | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Optimization Aided Design - Reinforced Concrete | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge in structural engineering, mechanics of beam and truss structures, reinforced concrete design and material properties matrices.

**Learning goals / Competences**

The students should be able to understand and apply the fundamental principles in calculating and designing reinforced concrete (RC) members and structures. They should gain special knowledge in the application of optimization aided design for concrete engineering.

After successfully completing the module the students

- should understand the design of reinforced concrete structures and members as well as cross-sections using optimization methods
- should be able to derive and optimize RC structures and members for given constraints, e.g. design space, loads and boundaries

**Content**

The module includes the following topics:

- principles and safety concept
- bending design
- strut-and-tie-modelling
- fundamentals of structural optimization
- outer form finding for the identification of structures
  - using one or bi-material topology optimization
  - steering of stresses and material, respectively
- internal form finding for effective reinforcements
  - using continuum, truss or hybrid topology optimisation
- design of cross-sections using optimisation methods

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Written examination (90 min, 100%) / Optional seminar papers, partially with presentations, to get bonus points for the exam (60 hours, deadlines will be announced at the beginning of the semester)

**Requirement for the award of credit points**

Passed final module examination and passed Homework

**Module applicability** (in other study programs)

MSc. Computational Engineering

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr.-Ing. P. Mark, Assistants

**Further information**

## Adaptronics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP03/**ADAP** | 5 CP | 150 h | $2^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Adaptronics | | | 3 SWS (45 h) | 105 h | No Restrictions |

**Prerequisites**

Basic knowledge in Structural Mechanics, Control Theory and Active Mechanical Structures is of advantage.

**Learning goals / Competences**

Acquiring knowledge in fundamental control methods, structural mechanics and modeling and their application to the active control of mechanical structures.

After successfully completing the module, the students

- have basic knowledge in behavior and modeling of piezoelectric materials for adaptronic structures and systems,
- have knowledge in model development of mechanical structures for the control system design (linear time invariant systems in state space and transfer function form),
- are able to perform the model based system analysis in time and frequency domain,
- are able to design basic control structures with compensator and feedback gain systems,
- are able to independently simulate control systems (PID and pole placement controller),
- have knowledge in discrete-time control systems,
- are able to use Matlab/Simulink software and Toolboxes for the control system analysis, design and simulation.

**Content**

An overall insight of the modeling and control of active structures is given within the course. The terms and definitions as well as potential fields of application are introduced. For the purpose of the controller design for active structural control, the basics of the control theory are introduced: development of linear time invariant models, representation of linear differential equations systems in the state-space form, controllability, observability and stability conditions of control systems. The parallel description of the modeling methods in structural mechanics enables the students to understand the application of control approaches. For actuation/sensing purposes multifunctional active materials (piezo ceramics) are introduced as well as the basics of the numerical model development for structures with active materials. Control methods include time-continuous and discrete-time controllers in the state space for multiple-input multiple-output systems, as well as methods of the classical control theory for single-input single output systems. Differences and analogies between continuous and discrete time control systems are specified and highlighted on the basis of a pole placement method. Closed-loop controller design for active structures is explained. Different application examples and problem solutions show the feasibility and importance of the control methods for structural development. Within this course the students learn computer aided controller design and simulation using Matlab/Simulink software. Students will implement the acquired knowledge in the framework of a seminar paper related to the controller design supported by Matlab Software.

**Teaching methods / Language**

Lectures with exercises and tutorials (3h / week) / English

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|---|
| **Mode of assessment**<br>Written examination (90 min, 100%) / seminar paper (Workload for the seminar paper 30 hours, deadlines will be announced at the beginning of the semester) |
| **Requirement for the award of credit points**<br>Passed final module examination and passed seminar paper |
| **Module applicability**<br>MSc. Computational Engineering |
| **Weight of the mark for the final score**<br>5 % |
| **Module coordinator and lecturer(s)**<br>Prof. Dr.-Ing. T. Nestorović, Assistants |
| **Further information** |

## Nonlinear Finite Element Methods for Structures

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP04/FEM-II | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Advanced Finite Element Methods | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Finite Element Methods in Linear Structural Mechanics (CE-P05), Basic knowledge in Structural Mechanics

**Learning goals / Competences**

After successfully completing the module, the students understand the origins and implications of nonlinearities in structural mechanics

- are able to formulate and solve nonlinear engineering problems with the finite element method accounting for geometrical and material nonlinearities
- can perform structural analyses, where the linear (1st order) theory is not valid (e.g. cables,
- membrane structures, load bearing and stability analyses beyond limit loads), and they can assess the results.

**Content**

The main topics of the course are:

- formulation and finite element discretization of the basic equations for nonlinear materials and geometrically nonlinear analysis in structural mechanics
- development of algorithms for the solution of the underlying nonlinear material and structural equations
- application to analyze the structural behavior considering material nonlinearity and large deformations
- nonlinear stability analysis of structures

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Written examination (120 min, 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr. Roger A. Sauer, Assistants

**Further information**

## Computational Fluid Dynamics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP05/CFD | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Computational Fluid Dynamics | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge of: partial differential equations and their variational formulation, finite element methods, numerical methods for the solution of large linear and non-linear systems of equations

**Learning goals / Competences**

Students should become familiar with modern methods for the numerical solution of complicated flow problems. This includes: finite element and finite volume discretizations, a priori and a posteriori error analysis, adaptivity, advanced solution methods of the discrete problems including particular multigrid techniques.

After successfully completing the module, the students shall

- be familiar with the various equations describing fluid dynamics, in particular the Stokes equation, the compressible and incompressible Navier-Stokes equations and Euler, equations, as well as their scope and applicability,
- be able to select stable finite element discretizations for each type of equations and know its advantages, disadvantages, limitations and practical realization,
- know the convergence properties of the various methods and be able to describe when these convergence rates can be expected in practice,
- be able to formulate a posteriori error estimators and know how to use them to improve the efficiency of finite element methods.

**Content**

- 1) Modelization
  Velocity, Lagrangian / Eulerian representation; transport theorem, Cauchy theorem; conservation of mass, momentum and energy; compressible Navier-Stokes / Euler equations; nonstationary incompressible Navier-Stokes equations; stationary incompressible Navier-Stokes equations; Stokes equations; boundary conditions
- 2) Notations and auxiliary results
  Differential operators; Sobolev spaces and their norms; properties of Sobolev spaces; finite element partitions and their properties; finite element spaces; nodal bases
- 3) FE discretization of the Stokes equations, 1st attempt
  Stokes equations; variational formulation in {div u = 0}; non-existence of low-order finite element spaces in {div u = 0}; remedies
- 4) Mixed finite element discretization of the Stokes equations
  Mixed variational formulation; general structure of finite element approximation; an example of an instable low-order element; inf-sup condition; motivation via linear systems; catalogue of stable elements; error estimates; structure of discrete problem
- 5) Petrov-Galerkin stabilization
  Idea: consistent penalty term; general structure; catalogue of stabilizations; connection with bubble elements; structure of discrete problem; error estimates; choice of stabilization parameter

| |
|---|
| • 6) Non-conforming methods<br>Idea; most important example; error estimates; local solenoidal bases<br>• 7) Streamline formulation<br>Stream function; connection to bi-Laplacian; FE discretizations<br>• 8) Numerical solution of the discrete problems<br>General structure and difficulty; Uzawa algorithm; improved version of Uzawa algorithm; multigrid; conjugate gradient variants<br>• 9) Adaptivity<br>Aim of a posteriori error estimation and adaptivity; residual estimator; local Stokes problems; choice of refinement zones; refinement rules<br>• 10) FE discretization of the stationary incompressible Navier-Stokes equations<br>variational problem; finite elements discretization; error estimates; streamline-diffusion stabilization; upwinding<br>• 11) Solution of the algebraic equations<br>Newton iteration and its relatives; path tracking; non-linear Galerkin methods; multigrid<br>• 12) Adaptivity<br>Error estimators; type of estimates; implementation<br>• 13) Finite element discretization of the instationary incompressible Navier-Stokes equations<br>Variational problem; time-discretization; space discretization; numerical solution; projection schemes; characteristics; adaptivity<br>• 14) Space-time adaptivity<br>Overview; residual a posteriori error estimator; time adaptivity; space adaptivity<br>• 15) Discretization of compressible and inviscid problems<br>Systems in divergence form; finite volume schemes; construction of the partitions; relation to finite element methods; construction of numerical fluxes |
| **Teaching methods / Language**<br>Lecture (2h / week), Exercises (2h / week) / English |
| **Mode of assessment**<br>Written examination (120 min, 100%) |
| **Requirement for the award of credit points**<br>Passed final module examination |
| **Module applicability**<br>MSc. Computational Engineering |
| **Weight of the mark for the final score**<br>6 % |
| **Module coordinator and lecturer(s)**<br>Prof. Dr. P. Henning, Assistants |
| **Further information** |

## Inelastic Finite Element Method for Structures

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP06 | 6 CP | 180 h | 3rd Sem | winter term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Inelastic Finite Element Method for Structures | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge of tensor analysis, continuum mechanics and linear Finite Element Methods. Previous participation in the course Advanced Finite Element Methods is recommended and participation Object-Oriented Modeling and Implementation of Structural Analysis Software is advantageous.

**Learning goals / Competences**

After successfully completing the module the students will

- understand the fundamentals of dissipative processes in the context of modeling inelasticity in quasi-brittle materials, using concrete as the main example.
- learn the computational approaches for modeling elastoplastic, damage and friction behavior.
- be familiar with the concept of strain localization and localized failure, including their mathematical and numerical implications, as well as strategies to address them.
- gain practical experience with implementation and algorithmic treatment of inelasticity in the context of incremental-iterative nonlinear structural analysis.
- develop skills to select appropriate numerical methods and material models, including multi-scale approaches, for practical problems and critically assess their limitations.
- be able to perform incremental analyses of progressive structural failure, critically evaluate the results, and assess the key design parameters such as load and deformation at the onset of inelasticity and structural redundancy (plastic reserve/residual strength).

**Content**

The course is concerned with inelastic material models including their algorithmic formulation and implementation in the framework of nonlinear finite element method. Strain localization and localized failure will be explored in detail, focusing on their mathematical and numerical implications, as well as the strategies to address them. Further, the course covers the fundamental theory and implementation aspects of frictional contact. Special attention will be given to efficient algorithms for physically nonlinear structural analyses, including elastoplastic and damage models for quasi-brittle materials, as well as friction algorithms. While concrete serves as a primary example, these modeling approaches are equally applicable to other materials such as rocks, fiber composites, sea ice, bone, stiff soils, and wood. The course includes coding exercises and a final assignment, where students implement a selected inelastic model into a finite element program and apply it to nonlinear structural analysis.

**Teaching methods / Language**

Lecture including Exercises (4h / week) / English

**Mode of assessment**

Project work (implementation of an inelastic model into FE code) with final student presentation / bonus points for homework assignments

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

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|---|
| MSc. Computational Engineering, MSc. Bauingenieurwesen , MSc. Subsurface Engineering |
| **Weight of the mark for the final score**<br>- |
| **Module coordinator and lecturer(s)**<br>Prof. Dr. R. A. Sauer, Dr. Ing. Vladislav Gudžulić, Assistants |
| **Further information** |

<table>
<tr><td colspan="6">Numerical Methods and Stochastics</td></tr>
<tr><td>Module-No./Abbreviation<br>CE-WP08/NMS</td><td>Credits<br>6 CP</td><td>Workload<br>180 h</td><td>Term<br>2nd Sem.</td><td>Frequency<br>Summer term</td><td>Duration<br>1 Semester</td></tr>
<tr><td colspan="3">Courses<br>Numerical Methods and Stochastics</td><td>Contact hours<br>4 SWS (60 h)</td><td>Self-Study<br>120 h</td><td>Group Size:<br>No Restrictions</td></tr>
<tr><td colspan="6">Prerequisites<br>Basic knowledge of: partial differential equations, numerical methods and stochastics</td></tr>
<tr><td colspan="6">Learning goals / Competences<br>Students should become familiar with modern numerical and stochastic methods<br>After successfully completing the module, the students<br>• should be able to formulate and analyze data from a probabilistic perspective,<br>• should understand the theoretical aspects of FEM and FVM methods,<br>• should be familiar with modern iterative solvers for large systems of linear equations and their necessity for numerical PDE solving,<br>• should be familiar with standard methods for solving optimization problems.</td></tr>
<tr><td colspan="6">Content<br>Numerical Methods:<br>• Boundary value problems for ordinary differential equations (shooting, difference and finite element methods)<br>• Finite element methods (brief retrospection as a basis for further material)<br>• Efficient solvers (preconditioned conjugate gradient and multigrid algorithms)<br>• Finite volume methods (systems in divergence form, discretization, relation to finite element methods)<br>• Nonlinear optimization (gradient-type methods, derivative-free methods, simulated annealing)<br>Stochastics:<br>• Fundamental concepts of probability and statistics, such as random variables, univariate distributions & densities, descriptive statistics, parameter estimation, & law of large no<br>• Regression, such as univariate and multivariate linear regression, least-squares estimation, data transformations, qualitative predictors, and regularization<br>• Exploratory data analysis, such as qq-plots and summary statistics</td></tr>
<tr><td colspan="6">Teaching Methods / Language<br>Lectures (3h / week), Exercises (1h / week) / English</td></tr>
<tr><td colspan="6">Mode of assessment<br>Written examination (180 min, 100% )</td></tr>
<tr><td colspan="6">Requirement for the award of credit points<br>Passed final module examination</td></tr>
<tr><td colspan="6">Module applicability<br>MSc. Computational Engineering, MSc. Bauingenieurwesen</td></tr>
<tr><td colspan="6">Weight of the mark for the final score<br>6 %</td></tr>
<tr><td colspan="6">Module coordinator and lecturer(s)<br>Prof. Dr. M. Weimar, Prof. Dr. J. Lederer, Assistants</td></tr>
<tr><td colspan="6">Further information</td></tr>
</table>

## Numerical Simulation in Geotechnics and Tunneling

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP09/NSGT | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |

| Courses | Contact time | Self-study | Group Size |
|---|---|---|---|
| Numerical Simulation in Geotechnics and Tunneling | 4 SWS (60 h) | 120 h | - |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students are able to
implement numerical models of complex boundary value problems in geotechnical engineering and tunneling, creating the adequate geometrical models,
evaluate numerical models and their results in a critical way,

- acquire adequate knowledge in fundamentals of the finite element method to be able to adopt numerical simulation in design and control of geotechnical or tunneling problems with focus on the interactions between the soil and structures.

**Content**

The course deals with the numerical modeling of various geotechnical structures and tunnels:

- Overall insight to the numerical simulation of geotechnical problems by using the finite element method and concise review of simple constitutive models
- Introduction to Hardening Soil (HS) and Hardening Soil Small Strain (HSS) model and calibration of constitutive parameters of the HS and HSS model
- Simulation of lab tests and optimization of constitutive parameters
- Details for proper simulation in geotechnics by addressing constructional details, optimum discretization, boundary and initial conditions
- Fundamentals of contact elements and their applications in geotechnical modeling
- Considering water pressures in numerical simulations: soil-water interactions in drained, undrained, consolidation, and fully coupled hydromechanical analyses
- Creation of models, execution of calculations and analysis of results for various geotechnical boundary value problems: shallow foundations, retaining walls, excavation, embankments, consolidation, slope failure, tunneling
- Methods to validate and verify the reliability of numerical models by exploring the numerical outputs in space and time and the evaluation of numerical results
- Introduction to FE simulations with Plaxis 2D and numgeo
- Introduction to Finite Element Limit Analysis (FELA) and the FE software OptumG2
- Comparison of Plaxis2D, numgeo and OptumG2 for different boundary value problems
- Brief overview of other numerical methods (e.g. DEM, MPM, boundary element method)

**Teaching methods / Language**

Lectures (4 h/week) / English

**Mode of assessment**

Final written exam (180 min.)

**Requirement for the award of credit points**

Passed final module examination

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| **Module applicability**<br>MSc. Computational Engineering, MSc. Bauingenieurwesen, MSc. Subsurface Engineering |
| **Weight of the mark for the final score**<br>6 % |
| **Module coordinator and lecturer(s)**<br>Prof. Dr.-Ing. habil. T. Wichtmann (coordinator), Dr.-Ing. C. Schmüdderich |
| **Further information** |

| **Object-oriented Modeling and Implementation of Structural Analysis Software** | | | | | |
|---|---|---|---|---|---|
| **Module-No./Abbreviation**<br>CE-WP10/OOFEM | **Credits**<br>3 CP | **Workload**<br>90 h | **Term**<br>$2^{nd}$ Sem. | **Frequency**<br>Summer term | **Duration**<br>1 Semester |
| **Courses**<br>Object-oriented Modeling and Implementation of Structural Analysis Software | | | **Contact hours**<br>2 SWS (30 h) | **Self-Study**<br>60 h | **Group Size:**<br>No Restrictions |

**Prerequisites**

Finite Element Methods in Linear Structural Mechanics (CE-P05) and Modern Programming Concepts in Engineering (CE-P04)

**Learning goals / Competences**

The seminar connects the theory of finite element methods (FEM) and object-oriented programming. After successfully completing the module, the students

- can implement the theories and methods of the course 'Finite Element Methods in Linear Structural Mechanics' in an object-oriented finite element program and apply this program for the analysis of engineering structures,
- have developed a program for the computation of spatial truss structures,
- can verify the program using benchmark examples,
- gained deep insight into the most relevant aspects for the implementation within the FEM and possibilities of using object-oriented programming for numerical approaches.

**Content**

The main topics of the course are:

- short summary of the basics of FEM and project-oriented programming
- preparing a project with two parts
  - Part 1: students individually develop and verify an object-oriented finite element program for the linear analysis of spatial truss structures
  - Part 2: students can choose between different options, either, the application developed in the Part 1 is extended to more challenging problems (nonlinear analysis, other element types, etc.) or students switch to an existing object-oriented finite element package (e.g. Kratos) and develop an extension of that software (e.g. material models, element formulations)

**Teaching methods**

Block seminar / equiv. to 2h lecture

**Mode of assessment**

Project work and final student presentation (100 %)

**Requirement for the award of credit points**

Passed project work and final student presentation

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

3 %

**Module coordinator and lecturer(s)**

Prof. Dr. Roger A. Sauer, Assistants

**Further information**

## Applied Computational Simulations of Structures

| **Module-No./Abbreviation** | **Credits** | **Workload** | **Term** | **Frequency** | **Duration** |
|---|---|---|---|---|---|
| CE-WP11/ACSoS | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |

| **Courses** | **Contact hours** | **Self-Study** | **Group Size:** |
|---|---|---|---|
| a) Applied Finite Element Methods<br>b) Finite Element Methods in Linear Computational Dynamics | a) 2 SWS (30 h)<br>b) 2 SWS (30 h) | a) 60 h<br>b) 60 h | No Restrictions |

**Prerequisites**

Finite Element Methods in Linear Structural Mechanics (CE-P05), Recommended: Adaptronics (CE-WP03)

**Learning goals / Competences**

After successfully completing the module, the students

- have the ability to model structures using commercial finite element software and to verify and assess the simulation results,
- can generate simulation models for structures with static and dynamic loading and write reports,
- can handle digital interfaces between BIM and structural analysis software to convert CAD models into structural simulation models,
- can perform transient and dynamic analyses of materials and structures.

**Content**

a) *Applied Finite Element Methods*

The course deals with the application of finite element simulations in structural engineering. This includes:

- handling of commercial finite element software
- modeling methods and sources of modeling errors
- pre- and post-processing
- BIM-FE interfaces

b) *Finite Element Methods in Linear Computational Dynamics*

The following topics are part of the lectures and exercises:

- Basics of linear Elastodynamics and Finite Element Methods in Structural Dynamics
- Explicit and implicit integration methods with emphasis on generalized Newmark-methods
- Computer lab: Implementation of algorithms into Finite Element programs

**Teaching methods / Language**

a) Seminar (2 SWS) / English b) Exercises (1 SWS), Lectures (1 SWS) / English

**Mode of assessment**

Homework: Applied computational simulations of structures with static and dynamic loadings (60 hours, 100%), homework partially with presentations (60 hours, deadlines will be announced at the beginning of the semester)

**Requirement for the award of credit points**

Passed homework

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

6 %

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| **Module coordinator and lecturer(s)**<br>Prof. Dr. Roger A. Sauer, Assistants |
| **Further information** |

## Computational Plasticity

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP12/CoPla | 6 CP | 180 h | 2nd Sem. | Summer term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Computational Plasticity | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students

- remember the definitions of the classifications of mechanical behavior and to which materials the different types of behavior can be associated,
- understand the phenomenology and mechanisms of elastic and plastic behavior of crystalline materials,
- know the different types of plasticity models in solid mechanics,
- understand the basic concepts and the mathematical formulation of continuum plasticity and crystal plasticity,
- understand the basic concepts of the numerical implementation of plasticity models,
- can assess which method is most suited to solve a given mechanical problem,
- are able to implement and apply a numerical scheme for the solution of elasto-plastic problems within the finite element method,
- have basic knowledge about the use of homogenization methods to describe plasticity in polycrystals.

**Content**

- Basics of continuum mechanics and FEM
- Phenomenology and atomistic origin of elastic and plastic deformation
- Concepts of continuum plasticity (yield criterion, flow rule, isotropic and kinematic hardening)
- Rate dependent and rate-independent formulations of continuum plasticity
- Numerical solution schemes for elasto-plasticity (operator split, return mapping, consistent tangent modulus)
- Computational aspects of small and large strain formulations
- Concepts of crystal plasticity (dislocation slip, flow rule, hardening models, consistent tangent modulus)
- Plasticity of polycrystals (Sachs, Taylor and self-consistent model)
- Numerical solution schemes of the crystal plasticity method
- Structure, implementation and application of an Abaqus UMAT

**Teaching methods**

Lecture (2h / week), Exercises (2h / week) / Homework (60h) / English

**Mode of assessment**

Written examination (120 min, 100 %) / Bonus points for homework

**Requirement for the award of credit points**

Passed homework and passed final module examination

**Module applicability**

MSc. Computational Engineering, MSc. Maschinenbau, MSc. Materials Science and Simulation

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|---|
| **Weight of the mark for the final score**<br>6 % |
| **Module coordinator and lecturer(s)**<br>Prof. Dr. rer. nat. A. Hartmaier, Assistants |
| **Further information** |

## Advanced Control Methods for Adaptive Mechanical Systems

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP13/ ACMAMS | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Advanced Control Theory, Structural Control | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Adaptronics (CE-WP03), fundamentals of control theory and structural control.

**Learning goals / Competences**

Extended knowledge in adaptive mechanical systems, advanced control methods and their application for the active control of structures.

After successfully completing the module, the students

- have advanced knowledge in control systems design,
- are able to design full order observer of the states in a state space model,
- have basic knowledge in observation using Kalman filter,
- have basic knowledge in the system identification of state-space models,
- have knowledge in experimental modal analysis,
- are able to independently design a velocity feedback vibration suppression for basic mechanical structures.

**Content**

Advanced methods for the control of adaptive mechanical systems are introduced in the course. This involves the recapitulation of the fundamentals of active structural control and an extension to advanced control. Observer design is introduced as a tool for the estimation of system states. In addition to numerical modelling using the finite element approach, system identification is explained as an experimental approach. Theoretical backgrounds of the experimental structural modal analysis are introduced along with the terms and definitions used in signal processing. Experimental modal analysis is explained using the Fast Fourier Transform. Advanced closed loop control methods involving optimal discrete-time control, introduction of additional dynamic approaches for the compensation of periodic excitations and basic adaptive control algorithms are explained and pragmatically applied for solving problems of vibration suppression in civil and mechanical engineering.

**Teaching methods / Language**

Lecture (2h / week), exercises and practical work (2h / week) / English

**Mode of assessment**

Written examination (120 min, 100%) / seminar paper

**Requirement for the award of credit points**

Passed seminar paper and passed final module examination

**Module applicability**

MSc. Computational Engineering

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr.-Ing. T. Nestorović, Assistants

**Further information**

## Computational Wind Engineering

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP14/ CWE | 3 CP | 90 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Computational Wind Engineering | | | 2 SWS (30 h) | 60 h | No Restrictions |

**Prerequisites**

Modern Programming Concepts in Engineering (CE-P04), Fluid Dynamics (CE-P06),
Recommended: Computational Fluid Dynamics (CE-WP05)

**Learning goals / Competences**

The students acquire advanced skills of CFD methods for the computation of wind engineering problems such as

- mean wind parameters and turbulence characteristics for the assessment of local wind climates (incl. wind farm locations),
- wind pressures at surfaces for the determination of wind loads at structures,
- gaseous transport in the atmospheric boundary layer for the prediction of the dispersion of exhausts and particles.

After successfully completing the module, the students will be able to

- understand the broad scope of computational fluid dynamics and the thematic integration of computational wind engineering within,
- identify fluid dynamical mechanisms of observed flow phenomena and choose adequate and suitable CFD methods to explore and formulate engineering solutions for real flows,
- solve relevant technical problems in the field of computational wind engineering by means of applying CFD simulations,
- validate, verify, and assess the solutions and results of CFD simulations,
- transfer learned skills in media literacy, and digital competence through the completion of supervised and supported self-studies to other engineering activities.

**Content**

This course introduces the details and guidelines for the application of CFD methods in the field of wind engineering. Relevant problems for practical applications and solution procedures are investigated. The theoretical background is taught in the obligatory Fluid Dynamics course while this course aims at the practical application of CFD methods on various wind engineering problems. In general, the steady state RANS approach and the time dependent LES approach are used. The lectures and exercises include all necessary steps of a CFD simulation ranging from the creation of the geometry of the problem to the assessment and presentation of the results. During the semester, the commercial software package ANSYS CFX and the open source software OpenFOAM are used. The following working steps are explained and carried out:

- Generation of simple geometries and block structured grids and analysis of the influence of the quality of the mesh on the results of the simulation.
- Generation of complex geometries and unstructured numerical grids.
- Setting up simulations (Pre-Processing):
    - Choosing the right boundary conditions.
    - Choosing the correct turbulence models.
    - Deciding on the parameters of the finite volume method such as interpolation schemes for the convective term of the Navier-Stokes equation.
    - Adding source terms of exhaust for the investigation of pollution in the atmosphere.

- Application of the numerical solvers including parallel processing.
- Post processing of the most important characteristics of wind engineering flows and presenting them in an adequate manner:
- Analysis of mean velocity vector fields around structures.
- Analysis of mean and time dependent pressure distributions on the surface of structures that are exposed to wind to estimate the load due to wind.
- Analysis of the aerodynamic forces of lift and drag.
- Gaseous transport and dispersion in the atmospheric boundary layer for the prediction of the dispersion of exhausts and particles.

▪ Procedures for quality assurance in CFD simulations -Validation and verification methods.

**Teaching methods / Language**
Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**
Written examination (75 min, 100%)

**Requirement for the award of credit points**
Passed final module examination

**Module applicability**
MSc. Computational Engineering

**Weight of the mark for the final score**
3 %

**Module coordinator and lecturer(s)**
Prof. Dr.-Ing. R. Höffer, Dr.-Ing. U. Winkelmann

**Further information**

## Coupled Multiphysical Modeling and Simulations

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP15 / CMPMS | 6 CP | 180 h | 2nd/3rd Sem. | Winter/Summer term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Coupled Multiphysical Modeling and Simulations | 4 SWS / 60 h | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge of continuum mechanics and mechanical modeling of materials is strongly recommended.

**Learning goals / Competences**

Students should develop a strong understanding of coupled multiphysical systems and their modeling. After successfully completing the module, the students shall be able to

- comprehend the properties and behavior of thermomechanical, electromechanical, and electromagnetic systems
- develop mathematical and numerical models for coupled systems
- implement and apply numerical methods for the computational solution of multiphysical systems
- utilize software to solve coupled problems, with a clear understanding of the underlying methods, properties, and limitations
- use machine learning techniques for surrogate modeling of complex multiphysical processes

**Content**

- Constitutive laws for thermomechanics, electromechanics, and electromagnetics
- Analytical methods for the mechanics of functional materials
- Numerical techniques for multiphysics coupling and simulation
- Non-linear electromechanical and electromagnetic material behavior
- Size-dependent effects in electromechanical systems
- Machine learning techniques applied to functional materials
- Practical implementation of the numerical models
- Simulation of real-world, industry-relevant problems

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / Homework (40) / English

**Mode of assessment**

Final oral test of 30 minutes (100%) / Bonus points for homework

| |
|---|
| **Requirement for the award of credit points**<br>Passed oral test and passed homework |
| **Module applicability**<br>MSc. Computational Engineering |
| **Weight of the mark for the final score**<br>5 % |
| **Module coordinator and lecturer(s)**<br>Dr. S. Kozinov, Assistants |
| **Further information** |

## Computational Modeling of Membranes and Shells

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP16 /CMMS | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Computational Modeling of Membranes and Shells | | | 4 SWS / 60 h | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge of continuum mechanics (CE-P07) and linear Finite Element Methods (CE-P05) is strongly recommended.

**Learning goals / Competences**

After successfully completing the module the students

- can identify the elements of numerical models for membranes and shells and explain their mathematical-physical background
- are able to derive numerical discretization methods from these
- can extend the formulations discussed for membranes and shells to other constitutive laws, and implement them into existing software codes
- are able to assess the accuracy of the results of such codes

**Content**

The module includes the following topics:

1. Kinematics of membranes under large deformations
2. Constitutive laws for membranes
3. Membrane equilibrium in strong and weak form
4. Summary of isogeometric finite element methods
5. Numerical discretization methods for membranes
6. Extension to shell theories
7. Rotation-free discretization methods for Kirchhoff-Love shells
8. Implementation of the presented discretization methods

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / Homework (40h) / English

**Mode of assessment**

Final oral test of 30 minutes (100%)

**Requirement for the award of credit points**

Passed oral test and passed Homework

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

5 %

**Module coordinator and lecturer(s)**

Prof. Dr. Roger A. Sauer, Assistants

**Further information**

## Numerical Methods for Conservation Laws

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP17/NMfHCL | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Numerical Methods for Conservation Laws | | | 4 SWS / 60 h | 120 h | No Restrictions |

**Prerequisites**

Basic knowledge about: ordinary differential equations, numerical integration, and numerical methods for the solution of large linear and non-linear systems of equations

**Learning goals / Competences**

Students should attain familiarity with numerical methods for the solution of differential equations, in particular hyperbolic conservation laws. This includes understanding the notion of entropy solutions and being able to construct stable numerical schemes that are capable of finding such solutions.

After successfully completing the module, the students shall be able to

- design, implement and use numerical methods for computer solution of scientific problems involving differential equations,
- understand properties of different classes of differential equations and their impact on solutions and proper numerical methods,
- understand the different concepts of solutions to hyperbolic conservation laws and their physical interpretations, know how to select appropriate numerical methods that capture the physically correct solutions,
- use software for solving differential equations with understanding of fundamental methods, properties, and limitations.

**Content**

- Introduction to PDE's; classification of PDE's; well-posedness; outline of the course
- Heat equation Setting; well-posedness; space discretization; properties of the discretization; finite volumesin1D and 2D; stability of ODEs (repetition); time discretization
- First order hyperbolic equations and characteristics; example: Burgers equation; crash of characteristics; discontinuous solutions; basic discretizations; characteristics for linear advective systems; linear Riemann problems
- Basic discretizations finite volume methods; linearization of nonlinear conservation laws; boundary conditions
- Convergence theory for linear methods notation; convergence, consistency and stability; verifying stability: CFL numbers; Von Neumann analysis
- Weak solutions and viscosity solutions weak solutions; viscosity limits and modified equations; Lax entropy condition; applications of entropy conditions; explicit entropy solutions to Riemann problems; weak entropy conditions; entropy pairs
- Monotone schemes, Consistent methods; idea of monotone schemes; properties of monotone schemes; the Godunov scheme
- Higher Order Finite volume methods for non-linear hyperbolic equations Lax-Wendroff scheme; TVD schemes, slope/flux limiters

**Teaching methods / Language**

Lecture (3h / week), Exercises (1h / week) / Homework (30) / English

| |
|---|
| **Mode of assessment** |
| Written examination (120 min, 100%) |
| **Requirement for the award of credit points** |
| Passed final module examination |
| **Module applicability** |
| MSc. Computational Engineering |
| **Weight of the mark for the final score** |
| 6 % |
| **Module coordinator and lecturer(s)** |
| Prof. Dr. P. Henning, Assistants |
| **Further information** |
| |

## Computational Fracture Mechanics

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP19/CFM | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Computational Fracture Mechanics | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students

- remember the different types of brittle fracture and ductile failure of materials,
- understand the theoretical background of the different types of fracture models,
- are able to study the relevant literature independently,
- are able to choose appropriate fracture models and to implement them in a finite element environment,
- are able to independently simulate fracture including plasticity for a wide range of materials and geometries,
- can assess situations where cracks in a structure or component can be tolerated or situations in which cracks are not admissible.

**Content**

- Phenomenology and atomistic aspects of fracture
- Concepts of linear elastic fracture mechanics
- Concepts of elastic-plastic fracture mechanics
- R curve behavior of materials
- Concepts of cohesive zones (CZ), extended finite elements (XFEM) and damage mechanics
- Finite element based fracture simulations for static and dynamic cracks
- Application to brittle fracture & ductile failure for different geometries and loading situations

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / Homework (60h) / English

**Mode of assessment**

Written examination (120 min, 100%), bonus points for homework

**Requirement for the award of credit points**

Passed final module examination and passed homework

**Module applicability**

MSc. Computational Engineering, MSc. Maschinenbau, MSc. Materials Science and Simulation

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr. rer. nat. A. Hartmaier, Assistants

**Further information**

## Materials for Aerospace Applications

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP20/MAA | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Materials for Aerospace Applications | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successful completion of the module, students can

- recapitulate which high performance material systems are used for aerospace applications, how they are manufactured, and which microscopic mechanisms control their properties,
- explain and apply procedures for selecting and developing material systems for aerospace components, considering the specific requirements,
- decide which characterization and test methods to apply for qualifying materials and joints for aerospace applications and know how lifetime assessment concepts work,
- communicate, using technical terms in the field of aerospace engineering in English.

**Content**

The substantial requirements on materials for aerospace applications are „light and reliable“, which have to be fulfilled in most cases under extreme service conditions. Therefore, specifically designed materials and material systems are in use. Furthermore, joining technologies play an important role for the weight reduction and reliability of the components. Manufacturing technologies and characterization methods for qualifying materials and joints for aerospace applications will be discussed. Topics are:

- Loading conditions for components of air-and spacecrafts (structures and engines)
- Selecting and developing materials and material systems for service conditions in aerospace applications (e.g. for aero-engines, rocket engines, thermal protection shields for reentry vehicles, light weight structures for airframes, wings, and satellites)
- Degradation & damage mechanisms of aerospace material systems under service conditions
- Characterization and testing methods for materials and joints for aerospace applications
- Concepts and methods for lifetime assessment

**Teaching methods / Language**

Lecture (3h / week), Exercises (1h / week) / English

**Mode of assessment**

Written examination (120 min, exceptions approved by examination office: oral exam/ 30 min)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering, MSc. Maschinenbau

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr.-Ing. Johanna Waimann, Prof. Dr.-Ing. M. Bartsch, Assistants

**Further information**

- Recommended are basics in materials science and solid mechanics
- Script in English, additional literature announced during lecture

## Quantum Computing

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP21/QC | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Quantum Computing | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences:**

After successfully completing the module, the students

- are enabled to design and create programs for quantum computers,
- can critically evaluate quantum systems and quantum algorithms,
- can assess the benefit of using quantum effects in computations.

**Content**

The lecture covers the theory and application of quantum computing from a computer science perspective with a focus on the usage of today's quantum hardware.

The relevant basics of quantum mechanics including superposition, measurement, interference, entanglement and mathematical notation are introduced. The characteristics of quantum bits and registers are discussed, and the construction and properties of quantum gates and quantum circuits presented. Prominent examples for quantum algorithms are surveyed including algorithms based on quantum Fourier transformation (e.g. Shor's factoring), quantum search (e.g. Grover) and quantum solution of linear systems of equations (e.g. HHL). Current quantum computer hardware, including gate-based and adiabatic quantum computers, as well as quantum error correction are discussed.

An introduction to quantum programming languages and environments will be provided. Hands-on programming exercises and self-implemented quantum circuits in study projects are used to discuss and illustrate the theoretical content. Implementations are tested on quantum simulators and cloud-based quantum hardware.

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Study project and oral examination

**Requirement for the award of credit points**

Passed final project and passed oral examination

**Module applicability**

MSc. Computational Engineering

**Weight of the mark for the final score**

-

**Module coordinator and lecturer(s)**

Prof. Dr. A. Vogel, Assistants

**Further information**

| Case Study A | | | | | |
|---|---|---|---|---|---|
| **Module-No./Abbreviation**<br>CE-WP24/CaStu A | **Credits**<br>3 CP | **Workload**<br>90 h | **Term**<br>2nd/ 3rd Sem. | **Frequency**<br>Both terms | **Duration**<br>1 Semester |
| **Courses**<br>Case Study A | | | **Contact hours**<br>- | **Self-Study**<br>90h | **Group Size:**<br>1-3 |

**Prerequisites**

-

**Learning goals / competences**

After completion of the project work, the students

- will have gained experience in working on a problem individually or in small groups,
- are able to organize and coordinate the assignment of tasks independently under the supervision of an advisor,
- should have gathered new information and insights into the activities of practicing engineers while acquiring skills in innovative research fields,
- will be able to present technical projects, and to develop problem solution strategies, hence obtaining worthwhile communication skills.

**Content**

The project topic is usually determined by the respective lecturer or one of his/her assistants. In addition to this, students may also conduct project work on topics defined by companies from industry or official authorities. However, the project work must be completed under the supervision of one of the course's lecturers. The student -or a small group of students - conducts a project independently and presents the results in the form of a written report and optionally, an oral presentation (upon agreement with the respective lecturer).

The projects are usually devised to as to integrate interdisciplinary aspects such as

- noticing problems, describing them and formulating envisaged goals
- team-oriented and interdisciplinary problem solutions
- organizing and optimizing one's time and work plan
- literature research and evaluation as well as the consultation of experts
- documentation, illustration and presentation of results

**Teaching Methods / Language**

Independent work in seminar rooms and computer labs; testing plants, where applicable / English

**Mode of assessment**

Review of the project work and oral presentation

**Requirement for the award of credit points**

The project paper and presentation will be graded. For this purpose, the individual achievements of the students within the project groups are separately evaluated. The evaluation includes: written project paper with a final presentation (100%)

**Module applicability**

MSc. Computational Engineering

**Weight of the mark for the final score**

3 %

**Module coordinator and lecturer(s)**

Professors and assistants of the program

**Further information**

<table>
<tr><td colspan="6">High-Performance Computing on Multicore Processors</td></tr>
<tr><td>Module-No./Abbreviation<br>CE-WP25/HPCM</td><td>Credits<br>6 CP</td><td>Workload<br>180 h</td><td>Term<br>2nd Sem.</td><td>Frequency<br>Summer term</td><td>Duration<br>1 Semester</td></tr>
<tr><td colspan="3">Courses<br>High-Performance Computing on Multicore Processors</td><td>Contact hours<br>4 SWS (60 h)</td><td>Self-Study<br>120 h</td><td>Group Size:<br>No Restrictions</td></tr>
<tr><td colspan="6">Prerequisites<br>-</td></tr>
<tr><td colspan="6">Learning goals / Competences<br>After successfully completing the module, the students<br>• are enabled to design and create programs for multicore processors,<br>• can critically evaluate multi-threaded programs and shared-memory access patterns,<br>• can assess the benefits and challenges of multicore programming techniques.</td></tr>
<tr><td colspan="6">Content<br>The lecture addresses parallelization on multicore processors. Thread-based programming concepts and techniques, including pthreads, C++11 threads, OpenMP and SYCL, are introduced and best practices are highlighted using applications from scientific computing.<br>An overview of the relevant hardware aspects including multicore architectures and memory hierarchies is provided. An in-depth introduction to multi-threaded programming on multicore systems with special emphasis on shared-memory parallelization is given and parallelization patterns, thread management and memory access strategies are discussed.<br>In hands-on sessions, programming exercises are used to discuss and illustrate the presented content.</td></tr>
<tr><td colspan="6">Teaching methods / Language<br>Lecture (2h / week), Exercises (2h / week) / English</td></tr>
<tr><td colspan="6">Mode of assessment<br>Written examination (120 min., 100%)</td></tr>
<tr><td colspan="6">Requirement for the award of credit points<br>Passed final module examination</td></tr>
<tr><td colspan="6">Module applicability<br>MSc. Bauingenieurwesen, MSc. Subsurface Engineering, MSc. Angewandte Informatik</td></tr>
<tr><td colspan="6">Weight of the mark for the final score<br>6 %</td></tr>
<tr><td colspan="6">Module coordinator and lecturer(s)<br>Prof. Dr. A. Vogel, Assistants</td></tr>
<tr><td colspan="6">Further information</td></tr>
</table>

## High-Performance Computing on Clusters

| **Module-No./Abbreviation** | **Credits** | **Workload** | **Term** | **Frequency** | **Duration** |
|---|---|---|---|---|---|
| CE-WP26/HPCC | 6 CP | 180 h | 3rd Sem. | Winter term | 1 Semester |

| **Courses** | **Contact hours** | **Self-Study** | **Group Size:** |
|---|---|---|---|
| High-Performance Computing on Clusters | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students

- are enabled to design and create programs for parallel computing clusters,
- can critically evaluate distributed-memory systems and programming patterns,
- can assess the mathematical properties of iterative solvers and their scalability.

**Content**

The lecture deals with the parallelization on cluster computers. Distributed-memory programming concepts (MPI) are introduced and best-practice implementation is presented based on applications from scientific computing including the finite element method and machine learning.

Special attention is paid to scalable solvers for systems of equations on distributed-memory systems, focusing on iterative schemes such as simple splitting methods (Richardson, Jacobi, Gauß-Seidel, SOR), Krylov-methods (Gradient descent, CG, BiCGStab) and, in particular, the multigrid method. The mathematical foundations for iterative solvers are reviewed, suitable object-oriented interface structures are developed and an implementation of these solvers for modern parallel computer architectures is developed.

Numerical experiments and self-developed software implementations are used to discuss and illustrate the theoretical results.

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Written examination (120 min, 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen, MSc. Angewandte Informatik

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr. A. Vogel, Assistants

**Further information**

| **Machine Learning: Supervised Methods** | | | | | |
|---|---|---|---|---|---|
| **Module-No./Abbreviation**<br>CE-WP28/ ML:SM | **Credits**<br>6 CP | **Workload**<br>180 h | **Term**<br>$2^{nd}$ Sem. | **Frequency**<br>Summer term | **Duration**<br>1 Semester |
| **Courses**<br>Machine Learning: Supervised Methods | | | **Contact hours**<br>4 SWS / 60 h | **Self-Study**<br>120 h | **Group Size:**<br>No Restrictions |

**Prerequisites**

The course requires basic mathematical tools from linear algebra, calculus, and probability theory. More advanced mathematical material will be introduced as needed. The practical sessions involve programming exercises in Python. Participants need basic programming experience. They are expected to bring their own devices (laptops).

**Learning goals / Competences**

The participants understand statistical learning theory. They have basic experience with machine learning software, and they know how to work with data for supervised learning. They are able to apply this knowledge to new problems and data sets.

After successfully completing the module, the students

- understand the basics of statistical learning theory,
- know the most relevant algorithms of supervised machine learning, and are able to apply them to learning problems,
- know and understand the strengths and limitations of various learning models and algorithms,
- can apply standard machine learning software for solving learning problems.

**Content**

The field of machine learning constitutes a modern approach to artificial intelligence. It is situated in between computer science, neuroscience, statistics, and robotics, with applications ranging all over science and engineering, medicine, economics, etc. Machine learning algorithms automate the process of learning, thus allowing prediction and decision-making machines to improve with experience. This lecture will cover a contemporary spectrum of supervised learning methods. The course will use the flipped classroom concept. Students work through the relevant lecture material at home. The material is then consolidated in a 4 hours/week practical session.

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

The course applies a flipped classroom format. The sessions plan is largely based on the following caltech lectures: http://work.caltech.edu/telecourse.html

**Mode of assessment**

Written examination (90 min, 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering

**Weight of the mark for the final score**

6 %

**Module coordinator and lecturer(s)**

Prof. Dr. T. Glasmachers, Assistants

**Further information**

## Uncertainty Quantification in FE Analyses with Surrogate Modeling

| **Module-No./Abbreviation** | **Credits** | **Workload** | **Term** | **Frequency** | **Duration** |
|---|---|---|---|---|---|
| CE-WP29 | 6 CP | 180 h | $3^{rd}$ Sem. | Winter Semester | 1 Semester |

| **Courses** | **Contact hours** | **Self-Study** | **Group Size:** |
|---|---|---|---|
| a) Uncertainty Quantification<br>b) Surrogate Modeling | 2 h/week<br>2 h/week | 60 h<br>60 h | No Restrictions |

**Prerequisites**

Fundamental knowledge in structural analysis, Finite Element Method, probability theory, and basic programming (MATLAB, Python).

**Learning goals / Competences**

The course equips students with theoretical foundations and practical skills to model, propagate, and mitigate uncertainties in structural analysis. Students will be able to define an uncertainty quantification problem, evaluate the effect of aleatory, epistemic as well as polymorphic uncertainty onto computational models and to interpret the results. It delves into surrogate modeling methods that approximate high-fidelity simulations, enabling efficient uncertainty assessment in complex systems. Applications to structural reliability, optimization, and risk-informed decision-making are emphasized, with hands-on experience using state-of-the-art computational tools.

After successfully completing the modules, the students are able to

- Understand the role and significance of uncertainty in structural engineering and computational models.
- Apply probabilistic and non-probabilistic methods for modeling uncertain parameters.
- Develop and implement surrogate models for efficient uncertainty propagation and sensitivity analysis.
- Use state-of-the-art tools and frameworks to solve real-world problems involving uncertain data.

**Content**

a) Uncertainty Quantification

The course deals with the uncertain data involving in structural analysis:

- Fundamentals of uncertainty quantification: types and sources of uncertainty (aleatory vs. epistemic)
- Sources of uncertainty in structural engineering: material properties, geometry, boundary conditions, and external loads
- Computing with uncertainty models: stochastic model, interval analysis, fuzzy logic, and polymorphic model
- Evaluation of model responses due to uncertain inputs: Quantification by statistical measures, sensitivity analysis and structural reliability

b) Surrogate Modelling

The course deals with the development of numerical surrogate models to accelerate the computation with uncertain data:

- Surrogate models based on black-box machine learning techniques (Artificial Neural Network)
- Surrogate models based on reduced order methods (Proper Orthogonal Decomposition)
- Surrogate models based on hybrid combination (Physics-informed machine learning)

| |
|---|
| • Comparison of surrogate modelling techniques: accuracy vs. computational efficiency |
| **Teaching methods / Language**<br>a) Lectures (2 h/week) / English b) Lectures (2 h/week) / English |
| **Mode of assessment**<br>Final project work |
| **Requirement for the award of credit points**<br>Passed final module examination |
| **Module applicability**<br>MSc. Computational Engineering, MSc. Civil Engineering, MSc. Subsurface Engineering |
| **Weight of the mark for the final score** |
| **Module coordinator and lecturer(s)**<br>Dr.-Ing. B. T. Cao, Dr.-Ing. G. E. Neu, Assistants |
| **Further information** |

## Transient Finite Element and Finite Difference Methods

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP30/ TFEM | 6 CP | 180 h | 2nd Sem. | Summer Semester | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Transient Finite Element and Finite Difference Methods | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Finite Element Methods in Linear Structural Mechanics (CE-P05)

**Learning goals / Competences**

After successfully completing the module the students

- understand the mathematical formulations of transient problems, including ordinary differential equations (ODEs) and partial differential equations (PDEs)
- understand principles of numerical time integration schemes, their stability and accuracy
- learn to assess the validity of the simulations, and interpret physical implications
- gain hands-on experience in implementing numerical methods for transient problems

**Content**

a) Introduction to transient problems and analysis
  - Hamilton's principle and Euler-Lagrange differential equation
  - Classification of transient problems and applications in engineering
  - Overview of numerical approaches

b) Time integration of ODEs
  - Explicit and Implicit methods
  - Time integration of first order ODEs
  - Stability and accuracy analysis
  - Time integration of second order ODEs
  - Error estimates and Adaptive time stepping

c) Time integration of PDEs
  - Finite differences in space and time
  - Diffusion and wave equation

d) Outlook on Advanced topics in transient analysis
  - Fluid flow problems
  - Multiphysics problems

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Classroom quizzes, Homework assignments

**Requirement for the award of credit points**

Passed all quizzes and assignments

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

**Module coordinator and lecturer(s)**

Prof. Dr. Roger A. Sauer, Dr.-Ing. Sahir N. Butt

**Further information**

Can NOT be combined with CE-WP11 or BI-WP06

## Scientific C++ Programming (Basics)

| **Module-No./Abbreviation** | **Credits** | **Workload** | **Term** | **Frequency** | **Duration** |
|---|---|---|---|---|---|
| CE-WP31/DLE | 3 CP | 190 h | $1^{st}$ Sem. | Winter Semester | 1 Semester |
| **Courses**<br>Scientific C++ Programming (Basics) | | | **Contact hours**<br>2 SWS (30 h) | **Self-Study**<br>60 h | **Group Size:**<br>No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students

- are familiar with basic programming concepts and constructs in C++,
- are able to design and develop C++ applications and to work with C++ environments,
- can review and contribute to basic C++ projects.

**Content**

The lecture provides an introduction to C++ programming. Basics programming concepts such as types, statements, functions, pointers, memory management and data structures are introduced. Best practices as well as the organization and development of C++ projects are discussed. An introduction to C++ compilers, debugging concepts and development tools is provided.
In hands-on sessions, programming exercises are used to discuss and illustrate the presented content.

**Teaching methods / Language**

Block course (equiv. to 2 SWS) / English

**Mode of assessment**

Written examination (120 min., 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

-

**Weight of the mark for the final score**

**Module coordinator and lecturer(s)**

Prof. Dr. A. Vogel, Assistants

**Further information**

## Scientific C++ Programming (Advanced)

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP32/SCPA | 3 CP | 90 h | 2nd Sem. | Summer term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Scientific C++ Programming (Advanced) | 2 SWS (30 h) | 60 h | No Restrictions |

**Prerequisites**
-

**Learning goals / Competences:**
After successfully completing the module, the students

- are familiar with advanced programming concepts and constructs in C++,
- are able to design and develop modern C++ applications using latest language features,
- can review and contribute to advanced C++ projects.

**Content**
The lecture addresses advanced topics in C++ programming. Object-oriented programming concepts such as classes, inheritance and polymorphism as well as generic programming concepts such as templates are introduced. The standard template library (STL) and selected functionalities from C++14 and above are surveyed. Best practices as well as the organization and development of advanced C++ projects are discussed.
In hands-on sessions, programming exercises are used to discuss and illustrate the presented content.

**Teaching methods / Language**
Lecture, Exercise (2h / week)/ English

**Mode of assessment**
Written examination (120 min., 100%)

**Requirement for the award of credit points**
Passed final module examination

**Module applicability**
-

**Weight of the mark for the final score**
-

**Module coordinator and lecturer(s)**
Prof. Dr. A. Vogel, Assistants

**Further information**

## Deep Learning for Engineers

| **Module-No./Abbreviation** | **Credits** | **Workload** | **Term** | **Frequency** | **Duration** |
|---|---|---|---|---|---|
| CE-WP33/DLE | 6 CP | 180 h | $2^{nd}$ Sem. | Summer Semester | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Deep Learning for Engineers | | | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students

- have acquired fundamental skills and knowledge in deep learning, including training concepts and neural network architecture designs,
- are able to develop, train and employ deep learning models for scientific applications,
- can assess the benefits and limitations of neural networks for their projects.

**Content**

The lecture covers deep learning concepts and techniques, including:

- general ideas and mathematical background
- training and regularization methods
- neural network architectures
  (feed-forward, convolutional, physics-informed, autoencoder, ...)
- application to scientific and engineering problems
- employment on modern computer hardware

In hands-on sessions, practical exercises are used to discuss and illustrate the presented content.

**Teaching methods / Language**

Lecture (2h / week), Exercises (2h / week) / English

**Mode of assessment**

Written examination (120 min., 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

-

**Weight of the mark for the final score**

**Module coordinator and lecturer(s)**

Prof. Dr. A. Vogel, Assistants

**Further information**

## Advanced Discretization Methods

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-WP34/DLE | 3 CP | 90 h | 2nd Sem. | Summer Semester | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Advanced Discretization Methods | 2 SWS (30 h) | 60 h | No Restrictions |

**Prerequisites**

-

**Learning goals / Competences**

After successfully completing the module, the students

- have acquired a solid foundation in the mathematical formulations, implementation aspects and application of advanced discretization methods for the solution of partial differential equations, such as the finite cell method (FCM) and isogeometric analysis (IGA),
- understand the advantages and disadvantages of each method and can independently evaluate their suitability for a given situation,
- can apply their knowledge to the solution of various engineering and scientific problems.

**Content**

The lecture covers advanced discretization techniques beyond the conventional finite element methods for the solution of partial differential equations, such as the finite cell method (FCM) and isogeometric analysis (IGA). In each case the mathematical formulation as well as the implementation aspects of the method are discussed and contrasted with conventional methods. Furthermore, the strengths and shortcomings of each method are highlighted such that their suitability for a given problem can be evaluated.

**Teaching methods / Language**

Lecture, Exercise (2h / week) / English

**Mode of assessment**

Written examination (120 min., 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

-

**Weight of the mark for the final score**

**Module coordinator and lecturer(s)**

Prof. Dr. A. Vogel, Dr.-Ing. M. Saberi

**Further information**

# Optional Courses
# CE-W01 – W06

## Training of Competences (Part 1)

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-W01/ToC I | 4 CP | 120 h | $1^{st}$ Sem. | Winter term | 1 Semester |
| **Courses**<br>Training of Competences and German Language course | | | **Contact hours**<br>4 SWS / 60 h | **Self-Study**<br>60 h | **Group Size:**<br>No Restrictions |

**Prerequisites**

-

**Learning goals / competences**

After successfully completing the module, the students

- are able to employ at a minimum level all four skills (speaking, listening, reading and writing) in familiar universal contexts or shared knowledge situations such as greeting, small talk, shopping, making appointments, eating out, orientation, biography, healthcare etc.

**Content**

The learning goals of this German language course fulfill the special requirements of foreign students majoring in a subject that uses English as a teaching language. On a basic level, the main focus of the course lies on action-oriented speaking, listening, reading and writing comprehension so that the students learn to cope with everyday situations of their life in Germany. The classes consist of small groups, ensuring that students have ample opportunities to speak as well as having their individual needs attended to. All of our instructors are university graduates experienced in teaching DaF (Deutsch als Fremdsprache - German as a foreign language) and have been selected for their experience in working with students and their ability to make language learning an active and rewarding process. An optional intensive block course after the winter semester helps to activate and to intensify the newly acquired language skills.

**Teaching methods / Language**

Lectures including exercises (4 h / week) / Homework (20 h) / German

**Mode of assessment**

Written examination (120 min, 100%)

**Requirement for the award of credit points**

Passed final module examination

**Module applicability**

MSc. Computational Engineering, special offer for foreign students of the course

**Weight of the mark for the final score**

-

**Module coordinator and lecturer(s)**

University Language Center (ZFA) of Ruhr-University Bochum

**Further information**

## Training of Competences (Part 2)

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-W02/ToC II | 4 CP | 120 h | $2^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Training of Competences II | | | 4 SWS / 60 h | 60 h | No Restrictions |

**Prerequisites**
Participation on CE-W01 is obligatory

**Learning goals / competences**
After successfully completing the module, the students

- are able to employ at an intermediate level all four skills (speaking, listening, reading and writing) in familiar universal contexts or shared knowledge situations such as greeting, small talk, shopping, making appointments, eating out, orientation, biography, healthcare etc.

**Content**
The learning goals of this German language course fulfill the special requirements of foreign students majoring in a subject that uses English as a teaching language. The main focus of the course lies on intermediate level action-oriented speaking, listening, reading and writing comprehension so that the students learn to cope with everyday situations of their life in Germany. This course continues the learning goals of the module Training of Competences 1.

**Teaching methods / Language**
Lectures (4 h / week) / German

**Mode of assessment**
Written examination (120 min, 100%)

**Requirement for the award of credit points**
Passed final module examination

**Module applicability**
MSc. Computational Engineering, special offer for foreign students of the course

**Weight of the mark for the final score**
-

**Module coordinator and lecturer(s)**
University Language Center (ZFA) of Ruhr-University Bochum

**Further information**

## Case Study B

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-W03/CaStu B | 3 CP | 90 h | 2nd/ 3rd Sem. | Both terms | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Case Study B | | | - | 90h | 1-3 |

**Prerequisites**
-

**Learning goals / competences**
After completion of the project work, the students
- will have gained experience in working on a problem individually or in small groups,
- are able to organize and coordinate the assignment of tasks independently under the supervision of an advisor,
- should have gathered new information and insights into the activities of practicing engineers while acquiring skills in innovative research fields,
- will be able to present technical projects, and to develop problem solution strategies and will hence also obtain worthwhile communication skills.

**Content**
The project topic is usually determined by the respective lecturer or one of his/her assistants. In addition to this, students may also conduct project work on topics defined by companies from industry or official authorities. However, the project work must be completed under the supervision of one of the course's lecturers. The student - or a small group of students - conducts a project independently and presents the results in the form of a written report and optionally, an oral presentation (upon agreement with the respective lecturer).
The projects are usually devised to as to integrate interdisciplinary aspects such as
- noticing problems, describing them and formulating envisaged goals
- team-oriented and interdisciplinary problem solutions
- organizing and optimizing one's time and work plan
- literature research and evaluation as well as the consultation of experts
- documentation, illustration and presentation of results

**Teaching Methods / Language**
Independent work in seminar rooms and computer labs; testing plants, where applicable / English

**Mode of assessment**
Review of the project work and oral presentation

**Requirement for the award of credit points**
The project paper and presentation will be graded. For this purpose, the individual achievements of the students within the project groups are separately evaluated. The evaluation includes: written project paper with a final presentation (100%)

**Requirement for the award of credit points**
The project paper and presentation will be graded. For this purpose, the individual achievements of the students within the project groups are separately evaluated. The evaluation includes: written project paper / 75% (100% without a final presentation) and final presentation / 25% (optional)

**Module applicability**
MSc. Computational Engineering

**Weight of the mark for the final score**
-

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|---|
| **Module coordinator and lecturer(s)**<br>Professors and assistants of the program |
| **Further information** |

## Recent Advances in Numerical Modeling and Simulation

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-W04/RANMS | 2 CP | 60 h | 2$^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Recent Advances in Numerical Modeling and Simulation | | | 2 SWS (30 h) | 30 h | No Restrictions |

**Prerequisites**

Finite Element Methods in Linear Structural Mechanics (CE-P05)

**Learning goals / Competences**

After successfully completing the module, the students

- gain insight into the current research in the field of numerical methods in structural mechanics based on selected research topics,
- have skills on selected numerical simulation approaches and its application in engineering,
- have tested research-oriented working.

**Content**

During the course, selected topics in the field of numerical modeling and simulation in structural mechanics will be presented. The range of topics will be continuously updated to fit with the relevance of current research topics, e.g.:

- the Extended Finite Element Method
- Finite Cell methods
- Isogeometric Analysis
- Peridynamics

For each topic, the theory will be offered in the compact form with emphasis on the algorithms and specific numerical methods. Selected application examples will be demonstrated.

**Teaching methods / Language**

Seminar (2h / week), / English

**Mode of assessment**

Seminar presentation 'Recent Advances in Numerical Modellng and Simulation' (30 h, 100 %)

**Requirement for the award of credit points**

Passed seminar presentation

**Module applicability**

MSc. Computational Engineering, MSc. Bauingenieurwesen

**Weight of the mark for the final score**

-

**Module coordinator and lecturer(s)**

Prof. Dr. Roger A. Sauer, Assistants

**Further information**

## Machine Learning: Evolutionary Algorithms

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-W05/ML:SM | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Machine Learning: Evolutionary Algorithms | | | 4 SWS / 60h | 80 h | No Restriction |

**Prerequisites**
The course requires basic mathematical tools from linear algebra, calculus, and probability theory. More advanced mathematical material will be introduced as needed. The practical sessions involve programming exercises in Python. Participants need basic programming experience. They are expected to bring their own devices (laptops).

**Learning goals / Competences**
After successful completion of the course,

- participants know the most important classes of direct search methods and their components,
- participants have a deep understanding of evolutionary algorithms, especially for continuous problem,
- participants know typical problem difficulties and the corresponding algorithmic components addressing these,
- participants can perform elementary runtime analysis of randomized optimization methods and know the most relevant classes of convergence speeds,
- participants can implement optimizations methods and apply them to solve new problem.

**Content**
Broad overview of optimization methods.
Evolutionary optimization methods for black-box optimization.
Algorithmic components for ill-conditioning, multi-modality, noise, constraint handling, and multiobjective optimization.
Convergence and runtime analysis.

**Teaching methods**
Block seminar (equivalent to 2 SWS)

**Mode of assessment**
Final oral test of 30 minutes (100%)

**Requirement for the award of credit points**
Passed oral test

**Module applicability**
MSc. Computational Engineering

**Weight of the mark for the final score**
-

**Module coordinator and lecturer(s)**
Prof. Dr.-Ing. Johanna Waimann, Dr.-Ing. J. Franke

**Further information**

## Advanced Constitutive Models for Geomaterials

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-W06/ACMG | 6 CP | 180 h | $2^{nd}$ Sem. | Summer term | 1 Semester |

| Courses | Contact hours | Self-Study | Group Size: |
|---|---|---|---|
| Advanced Constitutive Models for Geomaterials | 4 SWS (60 h) | 120 h | No Restrictions |

**Prerequisites**

Fundamental knowledge in soil mechanics and numerical simulation in Geotechnics

**Learning goals / Competences**

After successfully completing the module, the students are able to

- model the material behavior of soil using suitable, advanced constitutive models,
- select suitable numerical methods and constitutive models for practical questions and assess limitations according to the selected approaches,
- calibrate the parameters of the advanced constitutive models and evaluate the model performance based on single integration point simulations

**Content**

The course deals with the introduction of advanced soil mechanical behavior and appropriate constitutive models allowing to capture advanced effects. Model formulations and parameter calibration for different soil model families are taught. In addition, an introduction to single integration point finite element simulations with Incremental Driver (ID) is provided and simulations of different laboratory tests are conducted with ID using different elasto-plastic and hypoplastic constitutive models.

Advanced soil mechanics:

- Critical state soil mechanics
- Crushable soil mechanics
- Unsaturated soil mechanics
- Soil memory effects and their modelling
- Clay structure and small-strain stiffness anisotropy
- Influence of temperature on soil behavior and its modelling

Sophisticated constitutive models for soils:

- Modified Cam-Clay model
- Sanisand
- Hypoplasticity with Intergranular Strain
- Clay Hypoplasticity
- Hypoplasticity for crushable soils
- Visco-hypoplasticity
- Barcelona Basic Model

**Teaching methods / Language**

Lectures (4 h/week) / English

**Mode of assessment**

- Final written exam (180 min.)
- Optional homework to achieve bonus points for the written exam

**Requirement for the award of credit points**

Passed final written exam

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|---|
| **Module applicability**<br>Master Computational Engineering, Master Civil Engineering |
| **Weight of the mark for the final score**<br>- |
| **Module coordinator and lecturer(s)**<br>Prof. Dr.-Ing. habil. T. Wichtmann (coordinator), Dr.-Ing. M. Tafili, Dr.-Ing. C. Schmüdderich |
| **Further information** |

# Master Thesis
# CE-M

## Master Thesis

| Module-No./Abbreviation | Credits | Workload | Term | Frequency | Duration |
|---|---|---|---|---|---|
| CE-M | 30 CP | 900 h | 4th Sem. | - | 1 Semester |
| **Courses** | | | **Contact hours** | **Self-Study** | **Group Size:** |
| Master's Thesis | | | - | - | |

**Prerequisites**
Students can start their Master's thesis if six from seven compulsory courses have successfully been completed and a minimum of 70 credits has been collected.

**Learning goals / competences:**
With the completion of the Master's thesis,

- the students acquire the ability to plan, organize, develop, operate and present complex problems in Computational Engineering,
- qualifies students are qualified to work independently in the field of Computational Engineering under the supervision of an advisor,
- the associated presentation serves to promote the students' ability to deal with subject-specific problems and to present them in an appropriate and comprehensible manner,

Further, it serves to prove whether the students have acquired the profound specialised knowledge, which is required to take the step from their studies to professional life, whether they have developed the ability to deal with problems from their in-depth subject by applying scientific methods, and to apply their scientific knowledge.

**Content**
The Master's thesis can either be theoretically-, practically-, constructively- or organisationally-oriented. Its topic is determined by the respective supervisor. The results should both be visualised and illustrated in writing in a detailed manner. This particularly includes a summary, an outline and a list of the references used within a specific thesis and obligatorily, an oral presentation.

**Teaching Methods / Language of Report**
Independent work in seminar rooms and computer labs; testing plants, where applicable. The topic of the Master's thesis is issued by a lecturer of the course. The student conducts research independently and presents the results in the form of a final written report and an oral presentation / English or German

**Modes of assessment**
Review of the Master thesis report and oral presentation (100%)

**Requirement for the award of credit points**
Successful evaluation (grade not lower than 4.0) of Master's thesis and oral presentation

**Module applicability**
MSc. Computational Engineering

**Weight of the mark for the final score**
40 %

**Module coordinator and lecturer(s)**
The Master's thesis may be issued and supervised by any habilitated, appointed or designated lecturer. External lecturers, who are not directly teaching in the CompEng course, have to apply for the position as 1st supervisor to the examination board.

**Further information**