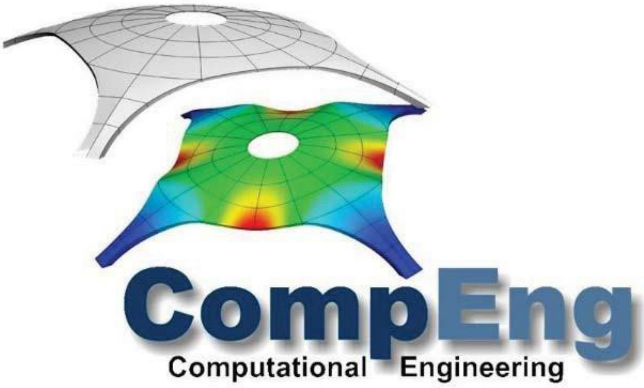
RUHR-UNIVERSITÄT BOCHUM

RUB

FAKULTÄT FÜR
BAU- UND UMWELT-
INGENIEURWISSENSCHAFTEN

Master‘s Program
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.

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	Modern Programming Concepts in Engineering	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-WP02	Optimization Aided Design - Reinforced Concrete	4	6	2
		CE-WP03	Adaptronics	3	5	2
		CE-WP04	Advanced Finite Element Methods	4	6	2
		CE-WP05	Computational Fluid Dynamics	4	6	2
		CE-WP06	Finite Element Methods for Nonlinear Analyses of Materials and Structures	2	3	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 Multi- and Manycore Processors	4	6	2
		CE-WP28	Machine Learning: Supervised Methods	4	6	2
		CE-WP13	Advanced Control Methods for Adaptive Mechanical Systems	4	6	3
		CE-WP14	Computational Wind Engineering	2	3	3
		CE-WP15	Design Optimization	4	6	3
		CE-WP17	Numerical Methods for Hyperbolic Conservation Laws	4	6	3
		CE-WP18	Safety and Reliabilty of Engineering Structures	4	6	3
		CE-WP19	Computational Fracture Mechanics	4	6	3
		CE-WP20	Materials for Aerospace Applications	4	6	3
		CE-WP26	High-Performance Computing on Clusters	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-W06	Advanced Constitutive Models for Geomaterials	2	3	2
		CE-W05	Machine Learning: Evolutionary Algorithms	4	6	2
		CE-W08	Quantum Computing	2	3	3
		CE-W09	An Introduction to Geostatistics	2	3	3
		CE-W03	Case Study B	2	3	2+3
			other relevant courses of the faculty or from engineering faculties of other universities			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**	

Stand: May 2022

Content

Compulsory Courses
CE-P01 - P07

<table>
<tr><td colspan="6">Mathematical Aspects of Differential Equations and Numerical Mathematics</td></tr>
<tr><td>Module-No./Abbreviation
CE-P01/MADENM</td><td>Credits
6 CP</td><td>Workload
180 h</td><td>Term
1st Sem.</td><td>Frequency
Winter term</td><td>Duration
1 Semester</td></tr>
<tr><td colspan="3">Courses
Mathematical Aspects of Differential Equations and Numerical Mathematics</td><td>Contact hours
4 SWS (60 h)</td><td>Self-Study
120 h</td><td>Group Size:
No Restrictions</td></tr>
<tr><td colspan="6">Prerequisites
No prior knowledge or preliminary modules. Basic calculus and experience with matrices.</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">Mode of assessment
Written examination (120 min, 100%)</td></tr>
<tr><td colspan="6">Requirement for the award of credit points
Passed final module examination</td></tr>
<tr><td colspan="6">Module applicability (in other study programs)
MSc. Computational Engineering</td></tr>
<tr><td colspan="6">Weight of the mark for the final score
4 %</td></tr>
<tr><td colspan="6">Module coordinator and lecturer(s)
Prof. Dr. G. Röhrle, Assistants</td></tr>
<tr><td colspan="6">Further information</td></tr>
</table>

Mechanical Modeling of Materials

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-P02/ MMoM	6 CP	180 h	1st 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	Contact hours	Self-Study	Group Size:
a) Basics of Analysis and Design, Numerical simulations in Steel Design, Fundamentals for computer-oriented Structural Analysis and Design assisted by Finite Element Analysis b) Stability Behavior – Members and Plated Structural Elements c) Structural Durability	4 SWS (60 h)	120 h	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

Stability Behavior of Slender Structures and Second Order Theory • Geometric non-linear design of structures - second order analysis • Buckling of linear members and frames • Lateral buckling and lateral torsional buckling • Eigenvalues and –shapes • Numerical methods for plate buckling *Structural Durability* • Fatigue • Modern Concepts of Fatigue Strength Design • Local Strain Concept • Crack Propagation Concept
Teaching methods / Language Lecture (2h / week), Exercises (2h / week) / English The course is partially conducted in the Blended Learning and Inverted-Classroom formats.
Mode of assessment Written examination (180 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. M. Knobloch, Assistants
Further information

Modern Programming Concepts in Engineering

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-P04/MPCE	6 CP	180 h	1st Sem.	Winter term	1 Semester
Course			**Contact hours**	**Self-Study**	**Group Size:**
Modern Programming Concepts in Engineering			4 SWS (60 h)	120 h	No Restrictions

Prerequisites
No prior knowledge or preliminary modules.

Learning goals / Competences:
In this course, students acquire fundamental skills for the development of software solutions for engineering problems. This comprises the capability to analyze a problem with respect to its structure such that adequate object-oriented software concepts, data structures and algorithms can be applied and implemented. In this course Java is used as a programming language. The conveyed solution techniques can be easily transferred to other programming languages.
After successfully completing the module, the students

- will have acquired fundamental skills for the development of software solutions employed in engineering problems,
- are capable of analyzing a problem with respect to its structure such that adequate object-oriented software concepts, data structures and algorithms can be applied and implemented,
- are able to code typical engineering programs in the Java programming language,
- can quickly and efficiently learn further programming languages needed in engineering based on the fundamental concepts presented in the course.

Content
Lectures and exercises cover the following topics:

- Principles of object-oriented modeling
  - Encapsulation
  - Polymorphism
  - Inheritance
- Unified Modeling Language (UML)
- Basic programming constructs
- Fundamental data structures
- Implementation of efficient algorithms
  - Vector and matrix operations
  - Solving systems of linear equations
  - Grid generation techniques
- Using software libraries
  - View3d as visualization toolkit
  - Packages for graphical user interfaces

During the exercises, students practice object-oriented programming techniques in the computer lab on the basis of fundamental engineering problems.

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

Weight of the mark for the final score 4 %
Module coordinator and lecturer(s) Prof. Dr.-Ing. M. König, 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,
- have knowledge to solve simple coupled problems (temperature, structural mechanics).

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, slices, beams, shells, three-dimensional volume elements for application in statics and dynamics,
- Finite element formulations for coupled (e.g. thermo-mechanical) problems,
- 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 (180 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

Module applicability

MSc. Computational Engineering, MSc. Bauingenieurwesen

Weight of the mark for the final score

4 %

Module coordinator and lecturer(s)

Prof. Dr. techn. G. Meschke, Assistants

Further information

Fluid Dynamics

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-P06/FD	3 CP	90 h	2nd 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

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 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 2 %
Module coordinator and lecturer(s) Prof. Dr.-Ing. R. Höffer, Assistants
Further information

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 • Material stability • Microstructures
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
Weight of the mark for the final score 4 %
Module coordinator and lecturer(s) Prof. Dr. rer. nat. K. Hackl, Assistants
Further information

Compulsory Optional Courses
CE-WP01 – WP28

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. rer. nat. K. Hackl, 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

<table>
<tr><td colspan="6">Adaptronics</td></tr>
<tr><td>Module-No./Abbreviation
CE-WP03/ADAP</td><td>Credits
5 CP</td><td>Workload
150 h</td><td>Term
2nd Sem.</td><td>Frequency
Summer term</td><td>Duration
1 Semester</td></tr>
<tr><td colspan="3">Courses
Adaptronics</td><td>Contact hours
3 SWS (45 h)</td><td>Self-Study
105 h</td><td>Group Size:
No Restrictions</td></tr>
</table>

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

Mode of assessment 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 Passed final module examination and passed Seminar paper
Module applicability MSc. Computational Engineering
Weight of the mark for the final score 5 %
Module coordinator and lecturer(s) Prof. Dr.-Ing. T. Nestorović, Assistants
Further information

Advanced Finite Element Methods

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

- are qualified to numerically solve nonlinear problems in engineering sciences by providing the methodological basis of the geometrically and physically nonlinear finite element method,
- are able to set up and implement simple models for damage analyses by user defined sub-programs,
- can perform structural analyses, where the 1^{st} order theory is not valid (e.g. cables, membrane structures, load bearing and stability analyses exceeding the load bearing capacity), 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 damage and large deformations
- algorithms for damage models within the finite element programs
- nonlinear stability analysis of structures
- finite element method for the solution of contact problems

Teaching methods / Language

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

Mode of assessment

Written examination (120 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

Module applicability

MSc. Computational Engineering, MSc. Bauingenieurwesen

Weight of the mark for the final score

6 %

Module coordinator and lecturer(s)

Prof. Dr. techn. G. Meschke, 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
  Idea; most important example; error estimates; local solenoidal bases
- 7) Streamline formulation
  Stream function; connection to bi-Laplacian; FE discretizations
- 8) Numerical solution of the discrete problems
  General structure and difficulty; Uzawa algorithm; improved version of Uzawa algorithm; multigrid; conjugate gradient variants
- 9) Adaptivity
  Aim of a posteriori error estimation and adaptivity; residual estimator; local Stokes problems; choice of refinement zones; refinement rules
- 10) FE discretization of the stationary incompressible Navier-Stokes equations
  variational problem; finite elements discretization; error estimates; streamline-diffusion stabilization; upwinding
- 11) Solution of the algebraic equations
  Newton iteration and its relatives; path tracking; non-linear Galerkin methods; multigrid
- 12) Adaptivity
  Error estimators; type of estimates; implementation
- 13) Finite element discretization of the instationary incompressible Navier-Stokes equations
  Variational problem; time-discretization; space discretization; numerical solution; projection schemes; characteristics; adaptivity
- 14) Space-time adaptivity
  Overview; residual a posteriori error estimator; time adaptivity; space adaptivity
- 15) Discretization of compressible and inviscid problems
  Systems in divergence form; finite volume schemes; construction of the partitions; relation to finite element methods; construction of numerical fluxes

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

Weight of the mark for the final score
6 %

Module coordinator and lecturer(s)
Prof. Dr. P. Henning, Assistants

Further information

Finite Element Method for Nonlinear Analyses of Materials and Structures					
Module-No./Abbreviation CE-WP06/FEM-III	**Credits** 3 CP	**Workload** 90 h	**Term** 2^{nd} Sem.	**Frequency** Summer term	**Duration** 1 Semester
Courses Finite Element Method for Nonlinear Analyses of Inelastic Materials and Structures			**Contact hours** 2 SWS (30 h)	**Self-Study** 60 h	**Group Size:** No Restrictions

Prerequisites

Basic knowledge of tensor analysis, continuum mechanics and linear Finite Element Methods is required; participation in the lecture „Advanced Finite Element Methods" (CE-WP04) is strongly recommended.

Learning goals / Competences

After successfully completing the module, the students

- know methods for the modeling of elastoplastic materials,
- have skills to select appropriate numerical methods and material models for practical problems and they can assess the limitations of the selected approaches.

Content

The course is concerned with inelastic material models including their algorithmic formulation and implementation in the framework of nonlinear finite element analyses. Special attention will be paid to efficient algorithms for physically nonlinear structural analyses considering elastoplastic models for metals, soils and concrete as well as damaged based models for brittle materials. As a final assignment, the formulation and implementation of inelastic material models into an existing finite element program and its application to nonlinear structural analyses will be performed in autonomous teamwork by the participants.

Teaching methods / Language

Lecture including Exercises (2h / week) / English

Mode of assessment

Project work (implementation of nonlinear material models) and final student presentation within the scope of a seminar (100%)

Requirement for the award of credit points

Passed project work and final student presentation

Module applicability

MSc. Computational Engineering

Weight of the mark for the final score

3 %

Module coordinator and lecturer(s)

Prof. Dr. techn. G. Meschke, Dr.-Ing. A. Alsahly, Assistants

Further information

Numerical Methods and Stochastics

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-WP08/NMS	6 CP	180 h	2nd Sem.	Summer term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Nuerical Methods and Stochastics			4 SWS (60 h)	120 h	No Restrictions

Prerequisites
Basic knowledge of: partial differential equations, numerical methods and stochastics

Learning goals / Competences
Students should become familiar with modern numerical and stochastic methods
After successfully completing the module, the students
- should be able to formulate and analyze data from a probabilistic perspective,
- should understand the theoretical aspects of FEM and FVM methods,
- should be familiar with modern iterative solvers for large systems of linear equations and their necessity for numerical PDE solving,
- should be familiar with standard methods for solving optimization problems.

Content
Numerical Methods:
- Boundary value problems for ordinary differential equations (shooting, difference and finite element methods)
- Finite element methods (brief retrospection as a basis for further material)
- Efficient solvers (preconditioned conjugate gradient and multigrid algorithms)
- Finite volume methods (systems in divergence form, discretization, relation to finite element methods)
- Nonlinear optimization (gradient-type methods, derivative-free methods, simulated annealing)

Stochastics:
- Fundamental concepts of probability and statistics, such as random variables, univariate distributions & densities, descriptive statistics, parameter estimation, & law of large no
- Regression, such as univariate and multivariate linear regression, least-squares estimation, data transformations, qualitative predictors, and regularization
- Exploratory data analysis, such as qq-plots and summary statistics

Teaching Methods / Language
Lectures (3h / week), Exercises (1h / week) / English

Mode of assessment
Written examination (180 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. M. Weimar, Prof. Dr. J. Lederer, Assistants

Further information

Numerical Simulation in Geotechnics and Tunneling

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

Courses	Contact time	Self-study	Group Size
a) Numerical Simulation in Tunneling b) Numerical Simulation in Geotechnics	2 h/week 2 h/week	60 h 60 h	No Restrictions

Prerequisites

Fundamental knowledge in soil mechanics and FEM

Learning goals / Competences

After successfully completing the modules, the students are able to

- implement numerical models of complex boundary value problems of tunnels and geotechnics, 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 problems with focus on the interactions between the soil and structures.

Content

a) Numerical Simulation in Tunneling

The course deals with the numerical modeling of tunnel structures and tunnel driving:

- basic aspects of numerical modeling of tunnel construction problems
- practical application of FE software environments to model a tunnel advance in 3D
- automatic and parameter-controlled generation of complex models

b) Numerical Simulation in Geotechnics

The course deals with the numerical modeling of geotechnical structures and construction methods:

- Overall insight to the numerical simulation of geotechnical problems by using the finite element method
- Details for proper simulation in geomechanics by addressing constructional details, optimum discretization, boundary and initial conditions
- Quick review of simple constitutive models, including calibration and discussion of important criteria to choose relevant constitutive models for distinct applications
- 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
- The soil-water interactions in drained, undrained and consolidation analyses, fully coupled hydromechanical finite element solutions
- Creation of models, execution of calculations and analysis of results for various geotechnical structures: shallow foundations, retaining walls, excavation, embankments, consolidation, slope failure
- Fundamentals of contact elements and their applications in geotechnical modeling
- Introduction to FE simulations with Plaxis 2D and other FE programs (Abaqus, Numgeo, etc.)
- Brief overview of other numerical methods (e.g. DEM, MPM, boundary element method)

Teaching methods / Language

a) Lectures (2 h/week) / English b) Lectures (2 h/week) / English

Mode of assessment Final written exam in the computer lab (180 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. techn. G. Meschke, Dr.-Ing. B. T. Cao, Dr. A. A. Lavasan, Assistants
Further information

Object-oriented Modeling and Implementation of Structural Analysis Software

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-WP10/OOFEM	3 CP	90 h	2^{nd} Sem.	Summer term	1 Semester

Courses	Contact hours	Self-Study	Group Size:
Object-oriented Modeling and Implementation of Structural Analysis Software	2 SWS (30 h)	60 h	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. techn. G. Meschke, Prof. Dr.-Ing. M. Baitsch, 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 b) Finite Element Methods in Linear Computational Dynamics	a) 2 SWS (30 h) b) 2 SWS (30 h)	a) 60 h 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 %

Module coordinator and lecturer(s) Prof. Dr. techn. G. Meschke, Assistants
Further information

Computational Plasticity

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-WP12/CoPla	6 CP	180 h	2^{nd} Sem.	Summer term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Computational Plasticity			4 SWS (60 h)	120 h	No Restrictions

Prerequisites

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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

Weight of the mark for the final score 6 %
Module coordinator and lecturer(s) 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:

- 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.
  - Basics of turbulence models for engineering applications.
  - 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 or heat for the investigation of transport in the atmosphere and the urban environment.
  - 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.
  - Heat transfer in the urban environment.
- 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

Design Optimization

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-WP15/DO	6 CP	180 h	3rd Sem.	Winter term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Design Optimization			4 SWS (60 h)	120 h	No Restrictions

Prerequisites

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Learning goals / Competences

Goals include the acquisition of skills in design optimization and the ability to model, solve and evaluate optimization problems for moderately complex technical systems and other related optimization problems. The programming project increases the social skills that are necessary to successfully complete a team project. Also, the programming project allows students to transfer theoretical knowledge gained from the lecture into practical solutions solved with software.

After successfully completing the module, the students

- will have a basic understanding of the theoretical fundamentals of numerical and mathematical optimization problems,
- are able to apply optimization techniques to solve real world problems in engineering, computer science and other fields with mathematical specifications,
- will be able to discuss optimization problems and possible solutions with expert team members as well as informed laypersons,
- can evaluate optimization problems by selecting applicable optimization techniques and implement solutions using state-of-the-art software frameworks,
- will be able to convey the importance of optimization to future clients, co-workers, managers.

Content

- Introduction: Definition of optimization problems
- Design of a process: conventional design, optimization as a design tool
- Optimization from a mathematical viewpoint: Numerical approaches, linear optimization, convex domains, partitioned domains
- Categories of opt. variables: Explicit design variables, synthesis and analysis, discrete and continuous variables, shape variables
- Dependent design variables
- Realization of constraints: Explicit and implicit constraints, constraint transformation, equality constraints
- Optimization criterion: Objectives in structural engineering
- Application of design optimization in structural engineering: trusses and beams, framed structures, plates and shells, mixed structures
- Solution techniques: Direct and indirect methods, gradients, Hessian Matrix, Kuhn-Tucker conditions
- Team Programming Project in Design Optimization (seminar paper)

Teaching methods / Language

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

Mode of assessment

Homework (presentation, 100%)

Requirement for the award of credit points Passed presentation
Module applicability MSc. Computational Engineering
Weight of the mark for the final score 6 %
Module coordinator and lecturer(s) Prof. Dr.-Ing. M. König
Further information

Numerical Methods for Hyperbolic 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 Hyperbolic 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

- 1st week:
  Introduction to PDE's; classification of PDE's; well-posedness; outline of the course
- 2nd – 3th week:
  Heat equation Setting; well-posedness; space discretization; properties of the discretization; finite volumesin1D and 2D; stability of ODEs (repetition); time discretization
- 4th – 5th week:
  First order hyperbolic equations and characteristics; example: Burgers equation; crash of characteristics; discontinuous solutions; basic discretizations; characteristics for linear advective systems; linear Riemann problems
- 6th week:
  Basic discretizations finite volume methods; linearization of nonlinear conservation laws; boundary conditions
- 7th –8th week:
  Convergence theory for linear methods notation; convergence, consistency and stability; verifying stability: CFL numbers; Von Neumann analysis
- 9th –10th week:
  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

• 11^{th} –12^{th} week: Monotone schemes, Consistent methods; idea of monotone schemes; properties of monotone schemes; the Godunov scheme • 13^{th} week: Higher Order Finite volume methods for non-linear hyperbolic equations Lax-Wendroff scheme; TVD schemes, slope/flux limiters • 14^{th} week: Summary /exam preparation
Teaching methods / Language Lecture (3h / week), Exercises (1h / week) / Homework (30) / English
Mode of assessment Written examination (120 min, 100%) / Homework
Requirement for the award of credit points Passed homework 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. P. Henning, Assistants
Further information

Safety and Reliability of Engineering Structures

Module-No./Abbreviation	**Credits**	**Workload**	**Term**	**Frequency**	**Duration**
CE-WP18/SRES	6 CP	180 h	3rd Sem.	Winter term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Safety and Reliability of Engineering Structures			4 SWS (60 h)	120 h	No Restrictions

Prerequisites

Basic knowledge in structural engineering

Learning goals / Competences

Basic knowledge of statistics and probability, a deeper understanding of the basic principles of reliability analysis in structural engineering, basic knowledge on how codes try to meet the reliability demands in regard to structural safety and serviceability, basic knowledge in simulation techniques.
After successfully completing the module, the students

- know how to specify and efficiently solve the failure integral for structural engineering design purposes by numerical integration and/or simulation,
- understand the basic philosophy behind the structural design codes in regard to safety and serviceability.

Content

- Introduction: causes of failures and basic definitions safety, reliability, probability, risk
- Basic demands for the design and appropriate target reliability values: Structural safety, Serviceability, Durability, Robustness
- Formulation of the basic design problem: R > E
- Strategies for the solution of the failure integral
- Descriptive statistics: position (mean value, median value), dispersion (range, standard deviation, variation coefficient), shape: (skewness, kurtosis), unbiased and biased estimators for describing parameters based on confined ensembles
- Identification of outliers
- Strategies to meet confidence demands for estimated design values based on confined ensembles
- Theoretical distributions: Discrete distributions (Bernoulli and Poisson Distribution), Continuous distributions (Rectangular, Triangular, Beta, Normal, Log-Normal, Exponential, Generalized Extreme Value Distributions, Generalized Pareto Distribution)
- Failure probability and basic design concept
- Code concept - level 1 approach
- First Order Reliability Method (FORM) - level 2 approach
- Full reliability analysis - level 3 approach
- Probabilistic models for actions: dead load, imposed loads, snow and wind loads, combination of loads
- Probabilistic models for resistance: cross section – structure
- Further basic variables: geometry, model uncertainties
- Strategies for effective Monte-Carlo Simulations: Pseudo-random numbers, basic transformation methods, correlated variables
- Vulnerability
- Probability distribution of the failure probability
- Non-linear analysis

Teaching methods / Language Lecture (2h / week), Exercises (2h / week) / Homework (45h) / English
Mode of assessment Written examination (120 min, 100%) / Project work on simulation techniques
Requirement for the award of credit points Passed project work and 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) PD Dr.-Ing. M. Kasperski
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. rer. nat. K. Hackl, 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

Case Study A

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-WP24/CaStu A	3 CP	90 h	2nd/ 3rd Sem.	Both terms	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Case Study A			-	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, 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 Multi- and Manycore Processors</td></tr>
<tr><td>Module-No./Abbreviation
CE-WP25/HPCM</td><td>Credits
6 CP</td><td>Workload
180 h</td><td>Term
2nd Sem.</td><td>Frequency
Summer term</td><td>Duration
1 Semester</td></tr>
<tr><td colspan="3">Courses
High-Performance Computing on Multi- and Manycore Processors</td><td>Contact hours
4 SWS (60 h)</td><td>Self-Study
120 h</td><td>Group Size:
No Restrictions</td></tr>
<tr><td colspan="6">Prerequisites
-</td></tr>
<tr><td colspan="6">Learning goals / Competences
After successfully completing the module, the students
are enabled to design and create programs for multi- and manycore processors,
can critically evaluate multi-threaded programs and shared-memory access patterns,
are able to survey advanced scientific topics independently and present their findings.</td></tr>
<tr><td colspan="6">Content
The lecture addresses parallelization for multi- and manycore processors. Thread-based programming concepts (pthreads, C++11 threads, OpenMP, OpenCL) are introduced and best-practice implementation aspects are highlighted based on applications from scientific computing.
In the first part, the lecture provides an overview on relevant data structures, solver techniques and programming patterns from scientific computing. An introduction to multi-threading programming on multicore systems is then provided with special attention to shared-memory aspects. Parallelization patterns are discussed and highlighted. Numerical experiments and self-developed software implementations are used to discuss and illustrate the presented content.
In the second part, students are assigned advanced topics for shared-memory computation from the engineering science including finite element methods and artificial intelligence. Based on a scientific paper, students present their topic to the lecture audience in form of a beamer presentation and numerical illustrations.</td></tr>
<tr><td colspan="6">Teaching methods / Language
Lecture (2h / week), Exercises (2h / week) / English</td></tr>
<tr><td colspan="6">Mode of assessment
Homework (100%, Presentation)</td></tr>
<tr><td colspan="6">Requirement for the award of credit points
Successful homework including presentation, Q&A session after presentation</td></tr>
<tr><td colspan="6">Module applicability
MSc. Computational Engineering, MSc. Bauingenieurwesen, MSc. Angewandte Informatik</td></tr>
<tr><td colspan="6">Weight of the mark for the final score
6 %</td></tr>
<tr><td colspan="6">Module coordinator and lecturer(s)
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	Credits	Workload	Term	Frequency	Duration
CE-WP28/ ML:SM	6 CP	180 h	2^{nd} Sem.	Summer term	1 Semester

Courses	Contact hours	Self-Study	Group Size:
Machine Learning: Supervised Methods	4 SWS (60 h)	120 h	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

Optional Courses
CE-W01 - W08

<table>
<tr><td colspan="6">Training of Competences (Part 1)</td></tr>
<tr><td>Module-No./Abbreviation
CE-W01/ToC I</td><td>Credits
4 CP</td><td>Workload
120 h</td><td>Term
1st Sem.</td><td>Frequency
Winter term</td><td>Duration
1 Semester</td></tr>
<tr><td colspan="3">Courses
Training of Competences and German Language course</td><td>Contact hours
4 SWS (60 h)</td><td>Self-Study
60 h</td><td>Group Size:
No Restrictions</td></tr>
<tr><td colspan="6">Prerequisites
-</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">Teaching methods / Language
Lectures including exercises (4 h / week) / Homework (20 h) / German</td></tr>
<tr><td colspan="6">Mode of assessment
Written examination (120 min, 100%)</td></tr>
<tr><td colspan="6">Requirement for the award of credit points
Passed final module examination</td></tr>
<tr><td colspan="6">Module applicability
MSc. Computational Engineering, special offer for foreign students of the course</td></tr>
<tr><td colspan="6">Weight of the mark for the final score
-</td></tr>
<tr><td colspan="6">Module coordinator and lecturer(s)
University Language Center (ZFA) of Ruhr-University Bochum</td></tr>
<tr><td colspan="6">Further information</td></tr>
</table>

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	2^{nd}/ 3^{rd} Sem.	Both terms	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Case Study B			-	90 h	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

-

Module coordinator and lecturer(s) Professors and assistants of the program
Further information

<table>
<tr><td colspan="6">Recent Advances in Numerical Modeling and Simulation</td></tr>
<tr><td>Module-No./Abbreviation
CE-W04/RANMS</td><td>Credits
2 CP</td><td>Workload
60 h</td><td>Term
2nd Sem.</td><td>Frequency
Summer term</td><td>Duration
1 Semester</td></tr>
<tr><td colspan="3">Courses
Recent Advances in Numerical Modeling and Simulation</td><td>Contact hours
2 SWS (30 h)</td><td>Self-Study
30 h</td><td>Group Size:
No Restrictions</td></tr>
<tr><td colspan="6">Prerequisites
Finite Element Methods in Linear Structural Mechanics (CE-P05)</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">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.</td></tr>
<tr><td colspan="6">Teaching methods / Language
Seminar (2h / week), / English</td></tr>
<tr><td colspan="6">Mode of assessment
Seminar presentation 'Recent Advances in Numerical Modellng and Simulation' (30 h, 100 %)</td></tr>
<tr><td colspan="6">Requirement for the award of credit points
Passed seminar presentation</td></tr>
<tr><td colspan="6">Module applicability
MSc. Computational Engineering, MSc. Bauingenieurwesen</td></tr>
<tr><td colspan="6">Weight of the mark for the final score
-</td></tr>
<tr><td colspan="6">Module coordinator and lecturer(s)
Prof. Dr.-techn. G. Meschke, Assistants</td></tr>
<tr><td colspan="6">Further information</td></tr>
</table>

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 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

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 optimization methods and apply them to solve new problems.

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. rer. nat. K. Hackl, Dr.-Ing. J. Franke

Further information

Advanced Constitutive Models for Geomaterials

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-W06/ACMG	3 CP	90 h	2nd Sem.	Summer term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Advanced Constitutive Models for Geomaterials			2 SWS (30 h)	60 h	No Restrictions

Prerequisites

Fundamental knowledge in soil mechanics and numerical simulation in Geotechnics

Learning goals / Competences

Within the module CE-WP09 (Numerical Simulation in Geotechnics and Tunneling), some basic and advanced constitutive models for geomaterials are introduced. In this course, further advanced constitutive models will be introduced and their relevance for different geotechnical applications will be discussed. One main objective of this course is to study the influence of different constitutive models on the numerical results for various geotechnical applications.

After successfully completing the module, the students are able to

- follow the mathematical formulation and implementation of advanced constitutive models,
- model the material behavior of soil using suitable, complex constitutive models,
- select suitable numerical methods and constitutive models for practical questions and assess limitations according to the selected approaches.

Content

The course extends the existing knowledge on soil behavior and its mathematical description:

- Hardening Soil, Hardening Soil Small Strain
- Modified Cam-Clay
- Softsoil Creep (SSC) model
- Hypoplasticity
- Viscohypoplasticity
- Bounding surface plasticity models SaniSand / SaniClay
- Calibration process of advanced constitutive models
- Effects of the constitutive model on the FE-prediction (selected examples)

Teaching methods / Language

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

Mode of assessment

Final student project with oral presentation (30 min, 100%)

Requirement for the award of credit points

Project work and final presentation

Module applicability

MSc. Computational Engineering

Weight of the mark for the final score

-

Module coordinator and lecturer(s)

Dr. A. A. Lavasan, Dr.-Ing. F. Prada, MSc. C. Schmüdderich

Further information

Quantum Computing

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-W08/QC	3 CP	90 h	3rd Sem.	Winter term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
Quantum Computing			2 SWS (30 h)	60 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), quantum solution of linear systems of equations (e.g. HHL) and quantum machine learning. Current quantum computer hardware 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

Block seminar (equiv. to 2 SWS) / English

Mode of assessment

Study project and oral examination

Requirement for the award of credit points

Passed final project and passed oral examination (100%)

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

An Introduction to Geostatistics

Module-No./Abbreviation	Credits	Workload	Term	Frequency	Duration
CE-W09/IGS	3 CP	90 h	3rd Sem.	Winter term	1 Semester
Courses			**Contact hours**	**Self-Study**	**Group Size:**
An Introduction to Geostatistics			2 SWS (30 h)	60 h	No Restrictions

Prerequisites

Fundamental knowledge of statistics and geotechnics

Learning goals / Competences:

In this module, students get familiar with the context of uncertainty in the multivariate spatial analysis required for geosciences. Theoretical aspects of processing, evaluation, and analysis of random spatial data and practical implementation are presented.

After successfully completing the module, the students

- will have a basic understanding of geostatistical methods as well as spatial interpolation methods needed to solve typical engineering geostatistical problems,
- can evaluate geostatistical problems and select appropriate mathematical methods and corresponding software to provide solutions that are both efficient and practical,
- can determine the type of geostatistical problem (stochastic or deterministic, analytic or numerical, range of randomness, etc.) and convey their knowledge to other engineers and workers,
- will be able to present their solutions of geostatistical problems to expert co-workers as well as clients and explain the significance of their solutions in an adequate manner.

Content

- Terminology and basics of geostatistics
- Spatial interpolation methods (deterministic and geostatistical methods)
- Mathematical techniques for modeling spatial variability (random field theory)
- Stochastic and deterministic processes to optimize monitoring design
- Possible applications and limits of geostatistical software

Teaching methods / Language

Lecture (2h / week) / English

Mode of assessment

Oral examination – Final project (30 min) / Final project will apply the gained knowledge during the lecture into a practical dataset (45 h)

Requirement for the award of credit points

Passed final project and oral examination

Module applicability

MSc. Computational Engineering

Weight of the mark for the final score

-

Module coordinator and lecturer(s)

Prof. Dr.-Ing. M. König, Dr.-Ing. E. Mahmoudi, Assistants

Further information

Master Thesis
CE-M

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