CVEN 4511-5511: Introduction to Finite Element Analysis

Meeting time, room, and zoom link: TuTh 9:30-10:45am, ECCE 1B41, and on Zoom (`https://cuboulder.zoom.us/j/99255062973`). Recorded lectures posted after class at `https://drive.google.com/drive/folders/1sAKd7zlf3GhmAoFMZ4bWWa9rNJ-Id3Pb`.

Instructor: Professor Richard Regueiro, 303.492.8026, `richard.regueiro@colorado.edu`; hybrid office hours (in-person in ECOT 421): Thursday, 12:30-2pm, `https://cuboulder.zoom.us/j/91694018096` .

Course Assistant: Mr. Thomas Allard, `thomas.allard@colorado.edu`; online office hours only: Monday, 4-5pm, `https://cuboulder.zoom.us/j/96833407838`

Course Description: The course covers theory and application of the linear, static and dynamic, finite element (FE) method for continuum physics, and solid and structural mechanics. We will work through, in detail, the formulation of finite element equations for a 1D, linear, axially-loaded bar: differential equation (strong form), integral or variational equation (with function spaces, the weak form), discrete approximation of weak form (Galerkin form), and the finite element equations (matrix form to solve numerically). We will derive shape functions and discuss spatial numerical integration. We will formulate and integrate numerically in time the 1D elastodynamics equations for transient dynamic analysis and discuss modal analysis. We will review briefly 2D structural frame analysis from the FE perspective (see CVEN 4525/5525 for more details). We will study linear heat conduction and linear elastostatics for 2D and 3D boundary value problems. Proper usage of finite elements and appropriate prescription of boundary conditions will be discussed. `Python` will be used to program and solve finite element equations for simple boundary value problems. You will complete an individual final project using (i) the finite element analysis (FEA) software package ABAQUS, or (ii) a theoretical project involving formulation and coding of linear finite element equations of your choosing. You may learn to use the ABAQUS user subroutine interface coded in Fortran. Usage of ABAQUS will be covered in separate Bechtel Lab sessions during class time or via pre-recorded tutorials posted on canvas.colorado.edu.

Course Objective: *To obtain sufficient understanding of the theory of the linear finite element method and its practical application in order to use commercial finite element software knowledgably, or to develop your own linear finite element code for analyzing continuum physics and solid mechanics (or structural mechanics) problems.*

Prerequisites: CVEN 3161 (Mechanics of Materials 1) and APPM 2360 (Introduction to Differential Equations with Linear Algebra), or equivalents; introductory structural mechanics and mechanics of materials, linear algebra, some basic coding experience. Python will be used. Review the tutorials on canvas.colorado.edu. Template code in Python, and pseudo-code, will be provided on canvas.colorado.edu for some problem sets. Mathematica can also be useful for analytical derivations (such as integration) and has its own short tutorials when opened.

**The course is taught at the 5000 graduate level. However, each problem set and the midterm exam may have additional or different problems for 5511 students versus 4511 students. The in-class midterm exam will be different for 4511 and 5511 students.*

Course Grading:

- 50% Problem sets will be due as a pdf file on canvas by 11:59pm on a day of the week depending on the length of a problem set and when it is given, but not every week. **No late problem sets will be accepted**; ask questions early and often!).

- 20% In-class mid-term exam (will be given Th, Oct 31, in-class). For remote students, please coordinate with Dr. Regueiro on taking the mid-term exam, if you cannot take it in-person.
- 25% Final project report due by 11:59pm, December 18, last day of the final exam period; five minute presentation delivered during the CVEN 4511-5511 course final exam period (December 14, 1:30-4pm) or scheduled separately.
- 5% Class participation: you may miss up to 2 class sessions without an excuse, and you must participate in "in-class" discussion in a constructive and meaningful manner.

Grading of coding assignments: Some Problem Sets have Python code-writing portions. Template Python code (and psuedo-code) will be provided for those who are not proficient programmers and thus need a start to their codes. When problem sets are graded, Dr. Regueiro will show his solution Python code in class (and recorded on zoom), but not provide the working code files themselves. You may receive up to 50% of points deducted due to non-working code after graded problem sets are returned and working Python code is shown on zoom (with recording available after each class with URL link on canvas), assuming you get your code to execute properly.

Problem sets:
-You may work together on problem sets (including code-writing in Python) but must turn in your own solutions. You are encouraged to try the problems yourself before working with other students. This will help you prepare for the in-class midterm exam (but there will be no programming on the midterm exam).
-Your solutions must be written clearly by hand, or typeset with an equation editor, such as MS Word, MathCad, LaTeX, etc. If your solutions are illegible because of poor handwriting, points will be deducted.

Rules for in-class midterm exam: The in-class midterm exam is Open Book, Open Notes. You are allowed to bring your laptop with electronic version of lecture notes, handouts, etc., but phones must be turned off. You may bring hardcopies of handouts and problem sets too.

References: course notes provided as pdf file.

- K.-J. Bathe, Finite Element Procedures, Prentice-Hall, 1995. TA347.F5 B36 1996 (reference on linear and nonlinear FEM).
- R.D. Cook, D.S. Malkus, M.E. Plesha, R.J. Witt, Concepts and Applications of Finite Element Analysis, 4th Edition, John Wiley & Sons, 2001. TA646 .C66 2002 (broad overview of linear and nonlinear FEM).
- J. Fish & T. Belytschko, A First Course in Finite Elements, Wiley, 2007 (brief, concise treatment of linear FEM).
- T.J.R. Hughes, The Finite Element Method: Linear Static and Dynamic Finite Element Analysis, Dover, 2000. TA347.F5 H84 2000 (detailed treatment of the mathematical theory of linear static and dynamic FEM).
- O.C. Zienkiewicz, R.L. Taylor, J.Z. Zhu, The Finite Element Method: Its Basis and Fundamentals, Seventh Edition, Elsevier, 2013. TA640.2 .Z5 2013 (encyclopedia on Intro FEM by two of the founders of the FEM).

Course Outline: (tentative, subject to change by the Instructor)

1. **Theory and programming of FE equations: Fish & Belytschko (F&B), Hughes (H), Notes posted**:
   (a) One-dimensional axially-loaded bar (F&B Ch 3, 4, 5; H Ch.1, Sect. 7.2, 7.3, Sect. 9.1, 9.2; Ch.1 of Notes): strong form, weak form, Galerkin approximation, finite element shape functions and equations; convergence and completeness; boundary conditions; multi-element assembly; natural coordinate and spatial numerical integration; dynamics and temporal numerical integration (Newmark's method); modal analysis.
   (b) Two-dimensional structural frames (brief review) (F&B 2.4, 10; H 1.16; Ch.2 Notes): Bernoulli-Euler beam finite element formulation; superposition of bar and beam finite element matrix equations into frame element; rotated element; 2D frame analysis; dynamics.
   (c) Two-dimensional linear heat conduction (F&B Ch 6, 7, 8; H Sect. 2.1-2.6, Sect. 7.1, Sect. 8.1; Ch.3 Notes) and analogy to groundwater flow: strong form to finite element equations; triangular and quadrilateral elements; isoparametric elements and spatial numerical integration; multi-element assembly; analysis of simple thermal problems; temporal numerical integration of parabolic equations (generalized trapezoidal rule).
   (d) Two- and three-dimensional linear elastostatics and dynamics (F&B Ch9; H Sect. 2.8-2.12, Ch3, Sect. 4.6, Sect. 7.2, 7.3, Sect. 9.1, 9.2; Ch.4 Notes): general three-dimensional, plane stress, plane strain, and axisymmetric formulations; strong form to finite element equations; hexahedral element; temporal numerical integration of hyperbolic equations (Newmark's method); modal analysis.

2. **Solving problems with ABAQUS or with your own code** (interspersed throughout the course in Problem Sets, and for the Final Project): The final project report will be due by the end of the final exam period (11:59pm, W, Dec 18), and you will deliver a short 5 minute presentation of your results sometime during the final exam period (TBD). You may work individually, or up to a maximum of 2 students per group on the Final Project. You will be required to meet with Dr. Regueiro in order to have your project idea approved. The objective of the project is:
   (i) to expose you to a finite element analysis experience using a commercial program (e.g., ABAQUS) that you may encounter while working in your research group, at a national laboratory, or at an engineering design and analysis firm,
   or (ii) to expose you to a research-oriented finite element programming experience (in Python, Julia, UMAT Fortran, FEniCS, or your own code, etc.). Those interested in more theoretical aspects of the FEM may choose the theoretical programming project option (ii) with the approval of Dr. Regueiro.

To learn more about the **methodology of verification and validation (V&V)** refer to the following (posted on canvas):

- Oberkampf et al. 2004, "Verification, validation, and predictive capability in computational engineering and physics," Appl. Mech. Rev. 57:345-84.
- Babuska & Oden 2004, "Verification and validation in computational engineering and science: basic concepts," Comput. Methods Appl. Mech. Engrg. 193:4057-4066.

- Schwer 2007, "An overview of the PTC 60/V&V 10: guide for verification and validation in computational solid mechanics," Engineering with Computers 23:245-252.
- 2019, "Verification & Validation of Computational Models Associated with the Mechanics of Materials," The Minerals, Metals & Materials Society.

These are assigned as self-reading for you to become familiar with the terms "verification" and "validation," and the difference between "calibration" and "validation." They have different meanings, although they are related.

Create your own 3DS account: (for accessing the online users manual and the learning edition software (limited to 1000 nodes and no user subroutines)) `https://www.3ds.com/edu/education/students/solutions/abaqus-le`

Abaqus online users manual (you need to enable your 3ds account first): `https://help.3ds.com/2023/English/DSSIMULIA_Established/SIMULIA_Established_FrontmatterMap/sim-r-DSDocAbaqus.htm?contextscope=all`

Honor Code:
Refer to the webpage:
`https://www.colorado.edu/sccr/students/honor-code-and-student-code-conduct`
If you violate the honor code, you will receive a failing grade of "F" for the course, regardless of the degree of academic dishonestly.

Special considerations: If you have a disability and require special accommodations, please provide Dr. Regueiro with a letter from Disability Services outlining your needs. Refer to the webpage `https://www.colorado.edu/disabilityservices`. If you have a conflict as a result of religious observances, notify Dr. Regueiro at least 2 weeks in advance of the assignment due date: `https://www.colorado.edu/oiec/religious-accommodations`

Review the required syllabus statements: `https://www.colorado.edu/academicaffairs/policies-customs-guidelines/required-syllabus-statements`

Bechtel Computing Laboratory: Refer to instructions posted on the door of ECCE 157 or 161, if you do not currently have Buff OneCard swipe access to the Bechtel Lab in ECCE 157, 161. Instructions for remotely accessing Bechtel computers for use of `ABAQUS` and `Jupyter Notebook (Python)` are provided here `https://oit.colorado.edu/services/learning-spaces-technology/computing-labs/remote-access`, and posted on canvas for using `Splashtop Business`.

***Sign here that you agree to the following:** "I have read, understand, and am willing to comply with the content of this Syllabus."