MAE4700/5700: Finite Element Analysis for Mechanical and Aerospace Design

Cornell University, Fall 2009

Lectures: PHL 403, TTh, 10:10-11:25 am

Recitations (ANSYS instruction)
Rhodes 471, Fr 1:25-2:15 pm

URL: http://mpdc.mae.cornell.edu/Courses/MAE4700/MAE4700.html

TEACHING STAFF

- Instructor: Prof. N. Zabaras, 101 Rhodes, zabaras@cornell.edu

- TA: Xiang Ma, xm25@cornell.edu

- ANSYS instructor: Dr. Rajesh Bhaskaran,102 Rhodes Hall, bhaskaran@cornell.edu

COURSE DESCRIPTION

- Introduction to linear finite element static and dynamic analysis for discrete and distributed mechanical and aerospace structures. Prediction of load, deflection, stress, strain, temperature and flow distributions.
- Major emphasis on underlying physics, mathematics, numerical methods and implementation.
- All homework assignments involve realistic numerical implementation of engineering problems using MATLAB based FEM software tools.
- Ansys will be used weekly to verify/reproduce MatLab calculations of one problem in each HW set. This problem will be discussed in your recitations.
- Design applications and large scale FEM projects are usually performed using ANSYS.

RateMyProfessor ANONYMOUS COMMENTS

- ✓ Interesting material. Professor Zabaras is one of the …. and …. professors I have had at Cornell. Lectures are enjoyable. Do NOT take this class if you do not plan to work very hard, but if you are looking to actually learn the material, this is THE class to take.

- ✓ This was the hardest course I have taken at Cornell. Zabaras expects hard work and genuine quality work. He has high expectations, but he is fair.

- ✓ Extremely difficult class, but if you put enough effort and time into it, it can be very rewarding. The lectures can be both impossibly confusing and extremely interesting, and I've been on both ends of the spectrum in this class. Pay attention, go to office hours, and put a lot of effort in, and it will be worth your while.

- ✓ Definitely one of my hardest classes at Cornell. Many hours spent and near-all nighters pulled. Useful class though. The subject is really good.

THIS IS NOT A COURSE ON HOW TO USE ANSYS. EMPHASIS ON FUNDAMENTALS OF THE THEORY & FEM IMPLEMENTATION AND ``CRITICAL USE" OF FEM IN ENGINEERING ANALYSIS & DESIGN

PREREQUISITES

- Senior or graduate student in Engineering or permission of instructor.
- The course will review and make extensive use of elementary principles from solid mechanics, heat transfer and fluid mechanics – in this course, you will find out how much you have learned (or not) in your earlier education at Cornell!
- Familiarity with calculus, differential equations and linear algebra is essential.
- The course will use MATLAB programming for all homework assignments and project. Access to MATLAB 7.0 or higher is required.

TEXTBOOKS

- No required textbook, class slides will become available on the course web site
- For those who will start complaining, a number of recommended references is given:
  - J. Fish and T. Belytschko, *A First Course in Finite Elements (2007).*
  - J. T. Oden, E. Becker, G. Carey, *Finite Elements: An Introduction. Vol. I (1981).*
  - J. N. Reddy, *An introduction to the finite element method (2005).*
  - K. H. Huebner et al., *The Finite Element Method for Engineers (2001).*
  - K.-J. Bathe, *Finite Element Procedures (Part 1-2) (Paperback) (1995).*
  - O. C. Zienkiewicz et al., *The FEM: Its Basis and Fundamentals, 6th Edition (2005).*
  - O. C. Zienkiewicz, R. L. Taylor, *The FEM for Solid & Structural Mechanics (2005).*
  - O. C. Zienkiewicz et al., *The FEM for Fluid Dynamics, 6th Edition (2005).*
  - T. J. R. Hughes, *The FEM: Linear Static & Dynamic Finite Element Analysis (2000).*

HOMEWORK

- About 12 HW sets – All HW problems involve MATLAB programming.

- **Group HW (3 students maximum) is strongly encouraged**. Homework done as a group will be graded as a group. Submit only one solution per group clearly listing the names of the group's members. Individual homework is discouraged.

- **Groups may change without need for any justification at any time during the semester**.

- All HWs need to be **typed and submitted electronically to MAE4700@gmail.com** by the designated time. We will not accept late homework.

EXAMS AND PROJECT

- Two prelims, no final (30% of the grade)
- Exam 1: 10/27/2009, Exam 2: 11/24/2009
- The final project (20% of the grade), with three students in each group, will involve an oral presentation (Dec. 5th) as well as a final report (6 pages + Appendices).
- For those registered for MAE 429 design credit, the final project needs to emphasize design applications. ANSYS is expected to be the main software used for design applications.
- Other non-design oriented projects may emphasize the (i) development of MATLAB FEM modules for applications beyond those discussed in class, or (ii) using ANSYS for challenging engineering applications.

OFFICE HOURS

- All office hours will take place in the Swanson Lab, Rhodes 163
  - Mond: 5:00-6:00 pm (Prof. N. Zabaras).
  - Tuesd: 8:00-9:00 pm (Xiang Ma).
  - Wedn: 4:00-5:00 pm (Dr. R. Bhaskaran, ANSYS)
  - Wedn: 5:00-6:00 pm (Prof. N. Zabaras)
  - Thur: 8:00-9:00 pm (Xiang Ma).
  - Frid: 2:20-3:30 pm (Dr. R. Bhaskaran, ANSYS)

COMPUTATIONAL MECHANICS

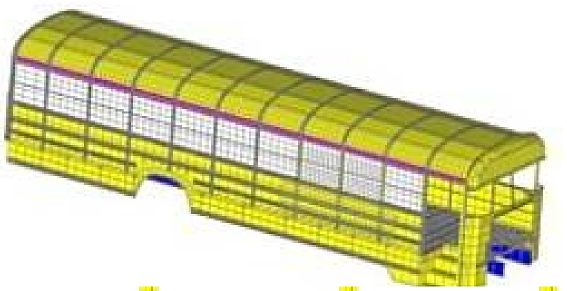
- A mature field that addresses the development of numerical methods for the solution of problems in mechanics (solids, fluids, etc.)
- Common computational mechanics methods:
  - FDM, Finite Differences methods
  - Finite Volume methods
  - FEM, Finite Element Analysis methods
  - BEM, Boundary Element Methods
  - Spectral methods
  - Mesh free methods
  - Many more ….

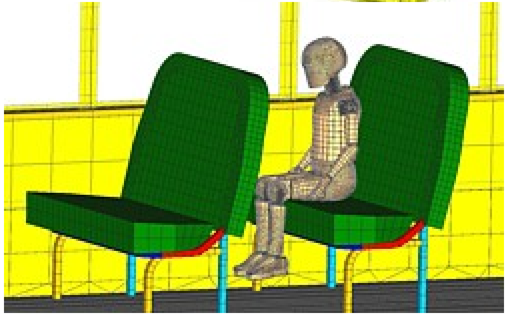
Brief history of FEM

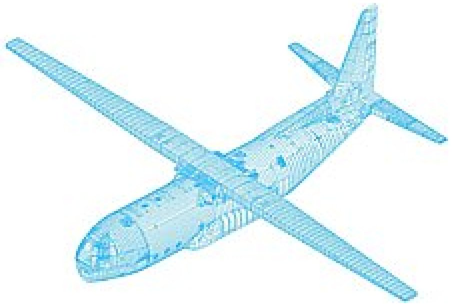
- R. Courant (1943) – variational methods to solve vibration problems.
- D. MacNeal (1965, NASA, NASTRAN development, MacNeal-Schwendler)
- J. Swanson (1969, Westinghouse Electric Corp, ANSYS)
- J. Hallquist (1989, LLNL, LS-DYNA)
- *Hibbitt*, Karlsson and Sorensen (1972, *ABAQUS*)
- FEM pioneers: O.C. Zienkiewicz (Swansea), R.H. Gallagher (Cornell), J. H. Argyris, E. Wilson, R. Taylor, J. T. Oden, T. J. R. Hughes, K.J. Bathe

WHAT IS FEM?

- A computational approach for solving problems governed by differential equations:
  - Solid and structural mechanics
  - Aerospace, electronic devices, automotive, nuclear
  - Fluid flow analysis, Heat transfer, Contamination, Environmental sciences
  - Electromagnetics, Acoustics
  - Biomechanics
  - Geomechanics, Seismic analysis
  - Quantum mechanics
  - Coupled physics problems (e.g. fluid/structure interaction)







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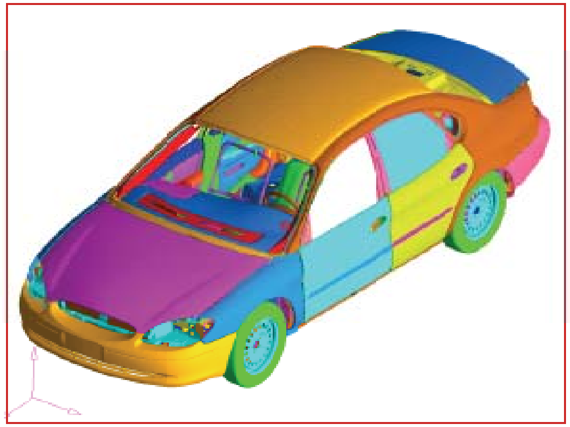
FEM ANALYSIS OF FORD TAURUS

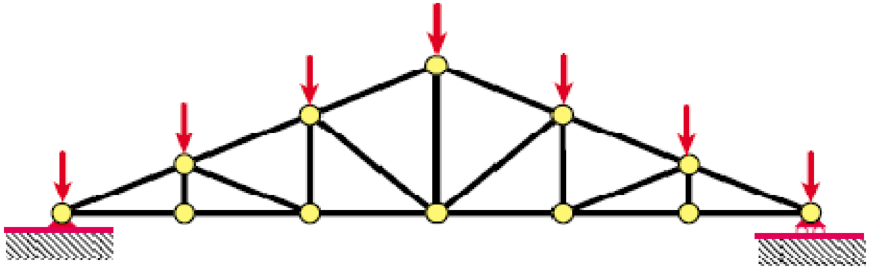


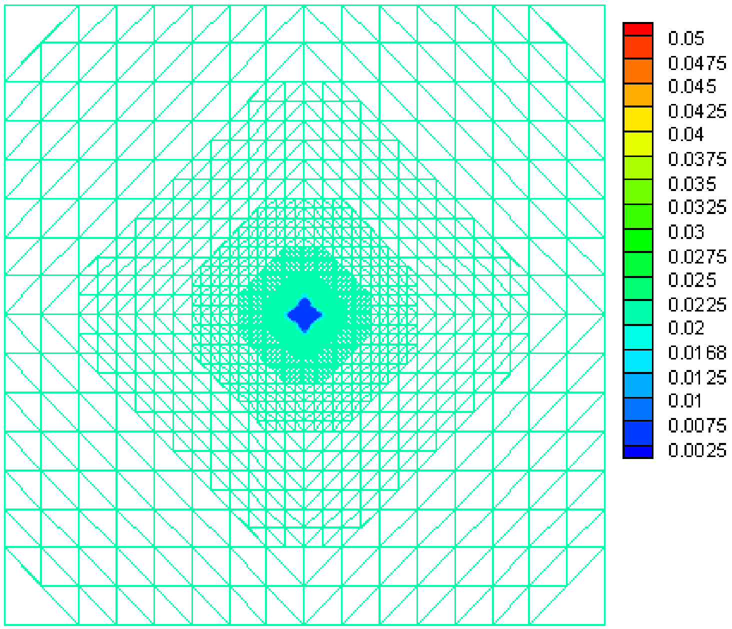
http://www.ncac.gwu.edu/vml/models.html

Number of Parts	- 778
Number of Nodes	- 936258
Number of Shells	- 805505
Number of Beams	- 4
Number of Solids	- 99486
Number of Elements	- 1057113

WHAT IS FEM?

- FEM introduces a piece-wise approximation to the governing equations.
- It discretizes the whole domain in `elements' and writes approximate eqs for each element.
- It then assembles the local equations.

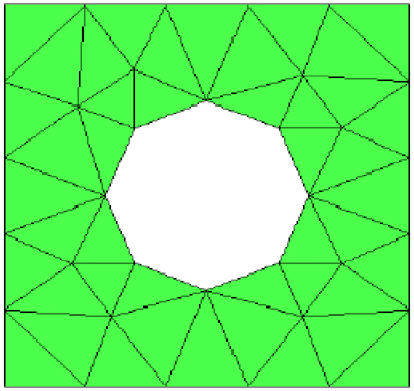




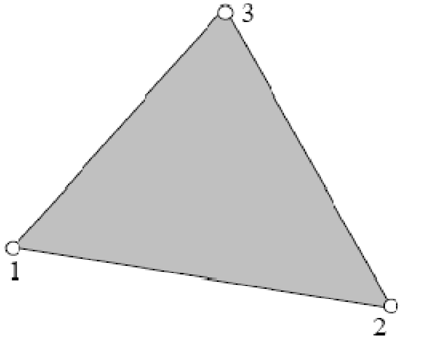
L. Tan and N. Zabaras (2007)

FEM for continuum problems

- We need to approximate the main (infinite number of) unknowns (e.g. velocity, $v(x,t), x \in B$) with a finite number of unknowns.
- In each discrete element of the domain, we interpolate the unknowns fields using their values at `the nodes' of the element.



- The nodes can be at the boundary or even inside each element!



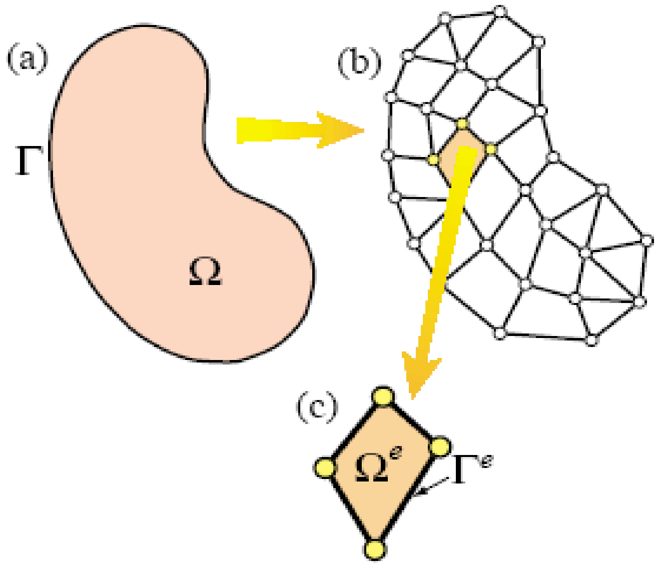
Approximating the governing Eqs in each element

- The course will address this for each application condidered.
- The success of the FEM lies on the fact that there is a common mathematical theory for approximating locally in each element the underlying governing equations
  - Direct approach (trusses, beams, etc.)
  - Variational approach
  - Galerkin approach (weighted residual)

These methods transform the original differential equation problem to an algebraic problem: Solving Ax=b

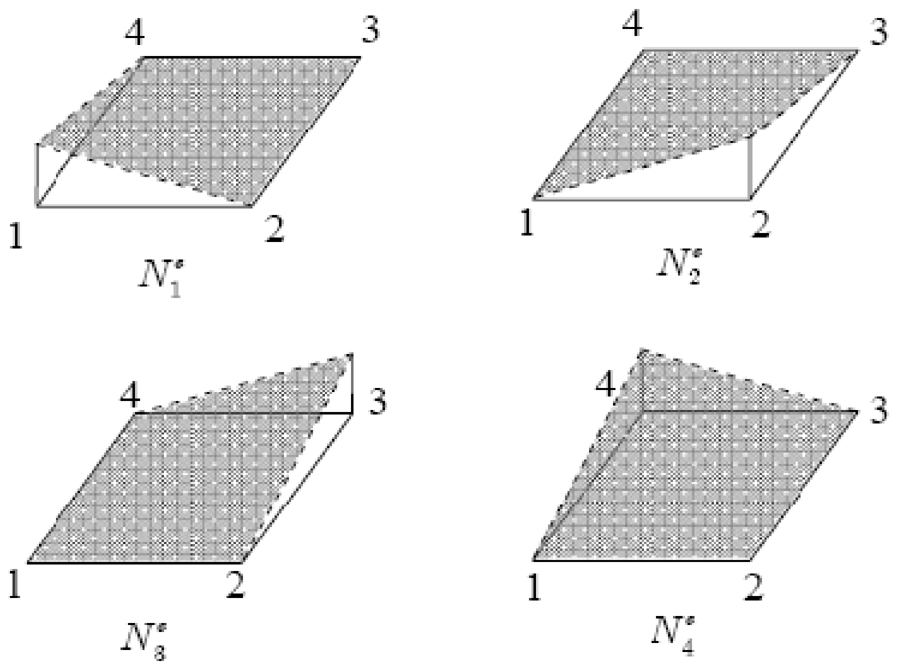
FEM overview: the common steps

- Step 1: Mesh generation: Discretize the domain in `elements'



FEM overview: the common steps

- Step 2: In each element, use interpolation functions to approximate your unknown fields in terms of `nodal values’

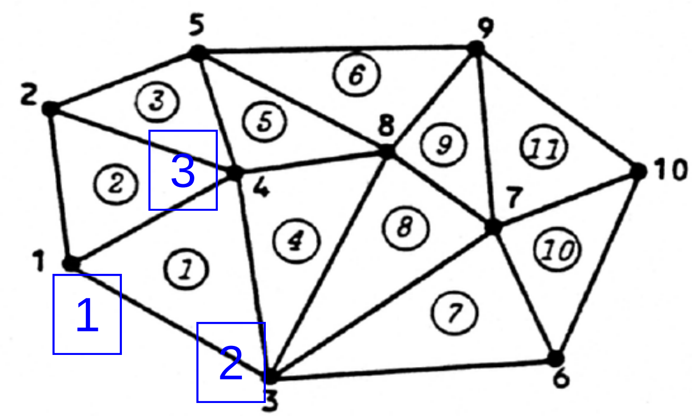


FEM overview: the common steps

- Step 3: Compute local form of the governing equations (e.g. Galerkin approximation)
  - Significant part of the course will be devoted on this task.

FEM overview: the common steps

- Step 4: Assemble the local equations in a global set of algebraic equations K u = F
  - Note in the fig. here that each triangular element has 3 nodes (1, 2, 3).
  - To assemble, you need to know to which global node each local node corresponds



  - Each column of the matrix T below represents this information!

Element connectivities

$$T = \begin{bmatrix} 1 & 1 & 2 & 3 & 4 & 5 & 3 & 3 & 8 & 7 & 7 \\ 3 & 4 & 4 & 8 & 8 & 8 & 6 & 7 & 7 & 6 & 10 \\ 4 & 2 & 5 & 4 & 5 & 9 & 7 & 8 & 9 & 10 & 9 \end{bmatrix}$$

FEM overview: the common steps

- Step 5: Apply boundary conditions (BC)
  - This can be complicated step if the boundary conditions are not directly in terms of the unknown field that you try to compute (e.g. traction/load BC when the unknowns are displacements)
  - Essential BC, Natural, Mixed, etc.
- Step 5: Solve the resulting system of algebraic equations
  - This can be numerically a critical step but we will say little about it in this class (CPU cost depends on this step!)
- Step 6: Postprocessing the results, e.g. compute stresses once displacements are known.

LINEAR AND NON-LINEAR FEM

- FEM becomes valuable for problems with no analytical solutions (i.e. for most engineering problems)
  - Solving the Navier-Stokes Equations
  - Solving deformation problems in complex geometries and with non linear material behavior (e.g. plastic deformation)

IN THIS INTRODUCTORY COURSE, WE WILL EMPHASIZE (MOSTLY) LINEAR FINITE ELEMENT ANALYSIS

Structural mechanics, linear static problems, heat transfer (but also … some basic fluid mechanics ..)

Our approach to FEM

- We will start with a simple approach: breaking our (mechanical) structure (e.g. a bridge, a frame) in components (truss elements, beam elements, …) and then proceed with the assembly and solution process
- We will then continue with a more mathematical approach using Galerkin approximations and discretizing differential equations (math is very important to this course)
- We will link the two methods when appropriate (mimimum potential energy, principle of virtual work, etc.)

Commercial FEM tools

- ANSYS
- ABAQUS: now part of Dassault Systèmes
- NASTRAN
- LS-DYNA
- ADINA

- Interface with CAD data bases – handle complex geometry
- Friendly graphical user interfaces
- User can input problem specific information while treating the main simulation as a black box
- A variety of finite element choices
- Mutliphysics

Why using MATLAB in the HWs of this course

- In earlier offerings of the course, there were practically no computing assignments
- In our class, ALL HW problems are computationally oriented – how can you learn a numerical method by doing hand calculations?
- The MATLAB programs are not perfect. However, they provide an ideal environment for:
  - Learning the fundamentals
  - Getting a first hand experience on what FEM does for the solution of realistic engineering problems
  - Allows you to put at work your knowledge from all earlier courses
  - We will expect that you understand the programs provided to a fine detail, being able to modify and extend them. It will be a lots of fun ….