Why to Study
Finite Element Analysis!

That is, “Why to take 2.092/3”

Klaus-Jürgen Bathe
Why You Need to Study Finite Element Analysis!

Klaus-Jürgen Bathe
Analysis is the key to effective design
We perform analysis for:

- deformations and internal forces/stresses
- temperatures and heat transfer in solids
- fluid flows (with or without heat transfer)
- conjugate heat transfer (between solids and fluids)
- etc...
An **effective design** is one that:

- performs the required task efficiently
- is inexpensive in materials used
- is safe under extreme operating conditions
- can be manufactured inexpensively
- is pleasing/attractive to the eye
- etc...
Analysis means probing into, modeling, simulating nature

Therefore, analysis gives us insight into the world we live in, and this

Enriches Our life

Many great philosophers were analysts and engineers …
Analysis is performed based upon the laws of mechanics

Mechanics

- Solid/structural mechanics (Solid/structural dynamics)
- Fluid mechanics (Fluid dynamics)
- Thermo-mechanics (Thermo-dynamics)
The process of analysis

1. Physical problem (given by a “design”)
2. Mechanical model
3. Solution of mechanical model
4. Interpretation of results
5. Design improvement
6. Change of physical problem
7. Improve model
8. Refine analysis

Flowchart:
- Physical problem (given by a “design”)
  - Mechanical model
    - Solution of mechanical model
      - Interpretation of results
        - Design improvement
        - Change of physical problem
          - Improve model
            - Refine analysis
Analysis of helmet subjected to impact

CAD models of MET bicycle helmets removed due to copyright restrictions.

New Helmet Designs
Analysis of helmet impact

Laboratory Test

ADINA Simulation Model

Head

Helmet

Anvil
Analysis of helmet subjected to impact

Comparison of computation with laboratory test results
In engineering practice, analysis is largely performed with the use of finite element computer programs (such as NASTRAN, ANSYS, ADINA, SIMULIA, etc...)
These analysis programs are interfaced with computer-aided design (CAD) programs Catia, SolidWorks, Pro/Engineer, NX, etc.
The process of modeling for analysis

1. Physical problem
2. Mathematical model governed by differential equations
3. Finite element solution
4. Interpretation of results
5. Refine analysis
6. Design improvements
   Structural optimization
7. Change of physical problem
8. Improve mathematical model
The process of modeling for analysis (continued)

Finite element solution of mathematical model

Choice of finite elements, mesh; representation of boundary conditions, etc.

Solve

Assessment of accuracy of finite element solution of mathematical model
Hierarchical modeling

Means taking increasingly more complex models to simulate nature with increasing accuracy

Increasingly more complex models

Assumptions:
- spring, rod, truss
- beam, shaft
- 2-D solid
- plate
- shell
- fully three-dimensional
dynamic effects
nonlinear effects

nature
CAD and Analysis

In CAD System

CAD solid model is established

In Analysis System

- Preparation of the mathematical model
- Meshing and Solution
- Presentation of results
CAD model of missile

ADINA
Finite Element Representation

ADINA
Pump
Finite Element Representation

Number of equations 1,040,049

Pump
Engine block - photo

Courtesy of AB Volvo Penta. Used with permission
Engine block - mesh

Courtesy of AB Volvo Penta. Used with permission
A **reliable** and efficient finite element discretization scheme should

- for a well-posed mathematical model

- **always** give, for a reasonable finite element mesh, a reasonable solution, and

- if the mesh is fine enough, an accurate solution should be obtained
Element Selection

We want elements that are reliable for any
- geometry
- boundary conditions
- and meshing used

The displacement method is not reliable for
- plates and shells
- almost incompressible analysis
Schematic solution results

solution sought

exact solution of mathematical model

$v=0.30$

$v=0.499$

$v=0.30$

$v=0.499$

$BAD !!!$

number of elements used
Example problem:
to show what can go wrong
Smallest six frequencies (in Hz) of 16 element mesh
Consistent mass matrix is used

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<th>16el. model Use of 2x2 Gauss integration</th>
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*Spurious mode (phantom or ghost mode)

Ref: Finite Element Procedures (by K. J. Bathe), Prentice Hall, 1996
Some analysis experiences
Tremendous advances have taken place –

• **mixed optimal elements** have greatly increased the efficiency and reliability of analyses

• **sparse direct solvers** and **algebraic multigrid iterative solvers** have lifted the analysis possibilities to completely new levels
In Industry:
Two categories of analyses

• Analysis of problems for which test results are scarce or non-existent
  – large civil engineering structures

• Analysis of problems for which test results can relatively easily be obtained
  – mechanical / electrical engineering structures
Examples of category 1 problems

• Analysis of offshore structures
• Seismic analysis of major bridges
  – only "relatively small" components can be tested

Reliable analysis procedures are crucial
Sleipner platform

Recall the catastrophic failure in 1991 of the Sleipner platform in the North Sea

• Ref. I. Holand, "Lessons to be learned from the Sleipner accident"

Proceedings, NAFEMS World Congress '97, Stuttgart, Germany, April 1997.
Heidrun platform

- The world's largest of its kind (in 1997)
- Probably due to the Sleipner accident, increased analysis attention was given to critical components
  - designers and analysts worked closely together
Correct surface stress prediction at critical locations is of vital importance for fatigue life determination.
Seismic analysis of major California bridges

- Damage from the 1989 and 1994 earthquakes
- Objective is to retrofit / strengthen the bridges (including the famous San Francisco-Oakland Bay Bridge)
Photo by Luis Alberto Higgins.
Photo by USGS.
Examples of category 2 problems

• Metal forming, crash and crush analyses in the automobile industries

• These types of problems can now be solved much more reliably and efficiently than just a few years ago
Roof crush analysis
Roof crush analysis
Roof crush analysis

ADINA
Roof crush analysis

- Total Applied Load vs Rigid Plate Displacement

- ADINA
- Roof Crush Test Data
Rolling
Multi-pass rolling

Material model:
- slab – aluminum, elastic-plastic material
- roll – rigid

ADINA:
- static, implicit analysis
- slab – 2160 u/p (4-node) elements, plastic-multilinear material model
- roll – 360 rigid contact segments
- contact algorithms – constraint-function
Rolling
multi pass rolling

Initial mesh

Final mesh
Bumper reinforcement

Bumper cross-section

molding (plastic)

reinforcement (steel)

Image from the Open Clip Art Library.
Stamping on a single action press, “springs” provide constant holding force.
Bumper reinforcement

Material data:
- steel, 1.8 mm
- friction coefficient, $\mu = 0.125$

ADINA
- static, implicit analysis
- 2750 MITC elements, 4-nodes
- plastic-multilinear material model
- rigid-target contact
Bumper reinforcement

ADINA

TIME 2.000

Effective plastic strain distribution
Bumper reinforcement

Final thickness distribution
Fluid-flows fully-coupled with structural interactions – an increasingly important analysis area

- Full Navier-Stokes equations for incompressible or fully compressible flows
- Arbitrary Lagrangian-Eulerian formulation for the fluid
Shock absorber
Shock absorber

Assembly parts

shock absorber = inner tube + metering tube + piston + outer tube
Shock absorber

Structural model
Shock absorber

Fluid mesh

3.2 in
Shock absorber

![Graph showing reaction force vs. stroke for shock absorber. The graph compares ADINA simulation data with experimental data. The force is measured in pounds (lb), and the stroke is in inches.]
Shock absorber
Lamp Internal Air Volume Mesh

- 200,000 Tet Elements
- Smooth Transitioning
- Localized Mesh Refinement
Lens Temperature

Predicted

Max 211

Measured

Max 206.1

* >248.0°F

* <100.0°F

240.0
220.0
200.0
180.0
160.0
140.0
120.0
100.0
Signal Housing Temperature

Predicted

Measured

Max 256

Max 237.4
Exhaust Manifold Mesh
Detail showing mesh mismatch
Plot of effective stress in the solid
Plot of pressure in the fluid
Fuel pump

![Graph showing the relationship between averaged mass flow (g/sec) and cam rotating speed (rpm). The graph includes data points from ADINA and measurements.](image_url)
Blood flow through an artery

Fluid mesh

Solid mesh
Blood flow through an artery
Blood flow through a stenotic artery

Image by the National Heart, Lung, and Blood Institute.
Blood flow through a stenotic artery
Analysis of an artificial lung

Artificial Lung

Courtesy of MC3. Used with permission.
Blood flow inlet

Fiber bundle – exchange CO$_2$ in blood with oxygen

Flow separator

Blood flow outlet

Particle trace plot
Analysis of an artificial lung
Particle trace
Radio-frequency tissue ablation

Electrode

Lesion

Courtesy of Medtronic, Inc. Used with permission.
Radio-frequency tissue ablation

Temperature variation during ablation cycle
So, why study finite element analysis? because --

You learn modern analysis techniques used widely in engineering practice and the sciences

You learn how to establish computational models of problems of solids and fluids, solve them on a laptop, and assess the accuracy of the results
You capitalize on your knowledge of mechanics, reinforce your knowledge, and solve problems that can only be tackled numerically on the computer.

Great knowledge in your “toolbox” whatever your goals!