Finite Element Modeling of the Human Form – Art and Science

CCSU Engineers’ Week
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Presentation Outline

- Overview of a small engineering consulting firm: CAE Associates.
- Finite element fundamentals.
- General applications – what we do.
- Analyses goals – why we do it.
- Application examples:
  - Aerospace.
  - Civil.
  - Manufacturing.
  - Legal.
- Modeling of the human form – bio-mechanical and marble.
  - Stents.
  - Bone remodeling.
  - Statue restoration.
CAE Associates

- Engineering consulting firm since 1981.
- One of first 4 ANSYS channel partners, since 1985.
CAE Associates Consulting Specialties

- **Structural analysis**
  - Linear and nonlinear
  - Static and dynamic
  - Implicit and explicit dynamics

- **Thermal analysis**
  - Linear and nonlinear
  - Steady-state and transient
  - Coupled thermal-flow

- **CFD**
  - Aerodynamics analysis, flow-field analysis
  - Turbo-machinery, propulsion
  - Chemical reacting flows, physical models

- **Custom software development**
The finite element method:
- Is a computer–aided mathematical technique.
- Is used to obtain an **approximate numerical solution** to the fundamental differential and/or integral equations that predict the response of physical systems to external effects.
- Was primarily developed by engineers using physical reasoning and can trace much of its origin to matrix methods of structural analysis.

**Physical System**

**F.E. Model with Loads and Boundary Conditions**
The key characteristics of the finite element method:

- Divides (discretizes) a continuous body into finite size sub-regions (elements).
- Assumes that the governing differential equations of the entire body are also valid for each individual element. These equations are transformed into equilibrium equations.
- Piece-wise solutions for the individual elements are found (instead of over the entire region).
- Elements are connected at the inter-element boundaries – continuity in terms of governing function and its derivatives between elements is not violated.
- Summation of element solutions provides the solution for the entire region.
The goals of a structural analysis are to determine how a structure responds mechanically when it is subjected to external or internal loads.

Solution items of interest include:
- Displacements
- Stresses
- Strains
- Reaction Loads

Categories of structural analysis include:
- Linear vs. nonlinear
- Static vs. dynamic
Nonlinear Structural Analysis

- Typical nonlinearities analyzed using finite elements include:
  - Geometric nonlinearities
    - Large strain
    - Large rotation
  - Material nonlinearities
    - Plasticity
    - Creep
    - Viscoelasticity
  - Change of Status
    - Contact
    - Birth and Death
A static structural analysis neglects the effect of the structure’s inertia on the solution.

From a practical perspective this means that the loading is being applied slowly enough, and the structure is responding slowly enough so that acceleration forces are negligible compared to elastic forces.

Examples where a dynamic analysis is required include:
- Vibration problems
- Impact/crash problems
Example of Dynamic Analysis

- Impact and penetration analysis of projectile.
General Finite Element Applications

- Will discuss structural applications only.

- Industries:
  - Aerospace.
  - Civil.
  - Manufacturing.
  - Legal.
  - Medical.
  - Other.
Analysis Goals

- Why perform finite element analysis?
  - Initial design support:
    - Can the design handle the expected loads?
    - Material selection.
  - Improvement and optimization:
    - Improve the design (less material, longer life).
  - Life prediction:
    - Is sometimes done as part of the initial design.
    - Can be done after a failure: failure/fatigue/fracture investigation.
Aerospace Applications

- Ceramic turbine vane.
  - Improve design of vane airfoils in terms of temperature range and weight.
  - Ceramics operate at higher temperatures and have lower density than metals.
  - Ceramics are more brittle.

- ASME paper: Development of Cooled, Ceramic First Stage Vanes for the FT8 Aeroderivative Gas Turbine by W. Day et al.
Aerospace Applications

- Automated crack propagation.
  - Developed with user-programmable features.
  - Technique morphs the mesh so that it lines up with crack direction, then the mesh is separated.
  - Application: Aging military aircraft evaluation.
Aerospace Applications

- Automated crack extension example:
Civil Applications

- Nuclear containment building repair.
  - Evaluating the repair process and effect on de-tensioning and re-tensioning cables.
  - Includes creep behavior of curing concrete.

7 day Creep - Change in radial displacement at 100 days creep (ft)
Civil Applications

- Concrete pipe cracking.
  - Special concrete elements used to predict cracking and crushing.
● NIST’s investigation into the WTC probable collapse sequence.
  – NIST NCSTAR 1-6
  – Structural Fire Response and Probable Collapse Sequence of the World Trade Center Towers
Civil Applications

- ANSYS thermal model used as input to thermal-stress analysis.
Civil Applications

- Truss local buckling

CTRUS3-13f (Gravity + temperature w/ const seq : static + dynamic analysis)
Civil Applications

NODAL SOLUTION
STEP = 11
SUB = 390
TIME = 38.733
USUM (AVG)
RSYS = 0
DMX = 19.802
SMX = 19.802

WTC-2 Severe Case Damage and Temperature Analysis
- NIST World Trade Center Tower 7 Collapse model.
Manufacturing Applications

- Buckling of corrugated cardboard boxes.
  - Design box to enable stacking without buckling.
Legal Applications

- Life prediction of solder in electronic chips due to thermal cycling.
  - Viscoplastic material model of solder during thermal cycling.
Three examples of finite element consulting projects that deal with biomedical and art restoration:

- Stent analysis and optimization.
- Bone remodeling.
- Analysis of restoration of Tullio's Adam statue.
What Does a Stent Do?

- A stent is a mechanical device laser cut from metal tubing that is used as a scaffold to hold open occluded vessels throughout the body.

Pre-procedure angiogram  Post-procedure angiogram
Example Stents

- Balloon and guide wire support the stent.
- Balloon expands stent.
- Plastic (permanent) strain in stent holds vessel open.
Stent Structural Design

- **Critical Issues:**
  - Maximize radial stiffness to best support the vessel.
  - Maximize surface area for drug coating.
  - Minimize recoil after deployment such that the stent stays in contact with the vessel wall.
  - Minimize the delivery size so that it can fit on the smallest possible catheter.
  - Maximize flexibility for ease in deployment.
  - Meet strength and fatigue requirements.

- Changing any one of these design variables may adversely affect others.
  - Example: increasing radial stiffness may decrease flexibility.
Finite Element Analysis of Stents

- FEA is a **requirement** to achieve Food & Drug Administration’s (FDA) approval for most devices that are implanted in the body.

- The structural nonlinearities inherent in stent design are:
  - Material nonlinearities
    - Plasticity
    - Super-elasticity (Nitinol)
    - Hyperelasticity (model of balloon and/or artery)
  - Geometric nonlinearities
    - Expansion/contraction many times the undeformed dimension
    - Localized large strains
  - Contact nonlinearities
    - Between stent and balloon
    - Between stent and artery wall
    - Between stent and itself (self-contact)
Solution Procedure for Stents

- **Solution steps:**
  - The polished laser cut tubing is starting point.
  - Crimp onto balloon.
  - Expansion to insertion diameter.
  - Released to vessel diameter.
    - Cyclic response for fatigue
    - Radial compression simulation

- Balloon typically modeled as non-compliant surfaces.
Bone remodeling is a natural, lifelong process in which old bone is absorbed and replenished by new bone.

The long term density of bone is strongly influenced by the level of mechanical stimulus it receives.

In the case of total knee and hip replacements, introduction of the prosthesis has the potential to alter load paths.

- Stress shielding is possible in bone which surrounds the prosthesis, resulting in reduction of bone density and loosening of device.
Bone remodeling rule relating the stimulus (strain energy density) to bone density and modulus was incorporated as a user-defined, nonlinear constitutive law.
- Predicts bone density change over time due to change in loading.
Bone Remodeling

- To test the accuracy of the model, a density bone scan was performed just prior to knee replacement.
  - This density distribution was then mapped onto the FE model as the starting, reference density.
- After approximately 7 months, a new bone scan was performed and compared to FE predictions.
Bone Remodeling

- Can also get the total mass of bone as a function of time:
Bone Remodeling

- Bone scans are typically done using DEXA (dual energy x-ray absorptiometry) scans, which are 2D images that show density variations.
- A post-processing procedure was developed to obtain similar density plots from ANSYS that can be compared to actual bone DEXA scans:
  - Select view direction.
  - Create ANSYS path plots at all points in a given grid covering the bone region.
  - Find average density along each path.
  - Include procedure to calculate density in particular regions.
Met's 15th-Century 'Adam' Shatters as Pedestal Collapses

By CELESTINE BOHLEN
Published: October 09, 2002

A 15th-century marble statue of Adam by the Venetian sculptor Tullio Lombardo crashed to the ground in the Velez Blanco Patio at the Metropolitan Museum of Art sometime Sunday evening, scattering its arms, legs and an ornamental tree trunk into dozens of pieces.

The statue's fall -- a museum's nightmare -- was confirmed yesterday morning by museum officials, who said they had delayed an announcement for a day while a preliminary investigation took place. The indoor patio, originally located in a castle in Spain, was screened off to the public yesterday as curators combed the tile floor for fragments. The museum barred news photographers from taking pictures, even from the balconies above.

Harold Holzer, the museum's chief spokesman, said the museum has now tentatively concluded that the 6-foot-3-inch statue fell to the ground when one side of the 4-inch-high base of its pedestal apparently buckled, tipping over both the pedestal and statue.

"We are reasonably certain that it collapsed inexplicably but on its own," Mr. Holzer said. The investigation is continuing, he added, but vandalism had been initially ruled out since there was no evidence of the statue itself having been struck or pushed.
Despite Assurances, Met Finds Artworks Aren’t Restored Overnight

Conservators have also used recently developed laser-mapping technology to create a three-dimensional “virtual Adam” that is being used to piece the work back together and also to allow engineers to determine the places within the sculpture that will undergo the most stress when it is standing again.
Statue Restoration

- **Analysis goal:**
  - Use finite element analysis to evaluate various repair approaches.

- **Additional information:**
  - Thousands of years experience in restoring marble statues.
  - Scanned-in CAD models of broken pieces of statue.
  - Brazil nut testing of adhesively-bonded marble.
  - Pin shear and pull-out testing.
  - Adhesive strength and creep testing (straining of adhesive over time).

![Diagram of a Brazil-out specimen](image-url)
Statue Restoration

- Complications:
  - Minimize permanent damage to statue, i.e. drilling holes.
  - Repair must consider:
    - Dead weight.
    - Vibration loads (trucks going down 5th Avenue),
    - Accidental bumping during transit.
    - Time-dependent creeping of adhesives.
  - If possible, make repairs reversible.
  - Stress singularity (stresses tend to infinity) exists at adhesively-bonded interfaces
    - Difficult to predict accurate stress at critical regions.
• Analysis of Brazil nut testing to correlate failure in full scale model.
  – The test results indicate that the fracture of the sample occurs along a path of maximum shear stress from the load location of the outer diameter to the maximum shear stress location on the elliptical hole.
  – The expected failure of the adhesive in the tests was rarely observed – most failure occurs in the marble.
  – Also provided accurate material model for the marble in the statue, including failure stress and behavior.
Statue Restoration

- General approach:
  - Create full model of statue before accident, determine stresses throughout due to dead weight.
    - This model predicts the load paths and stress distribution that withstood loads for 500 years.
  - Create full model of statue after accident with pieces bonded together.
    - This model will indicate any changes due to differences in geometry/stiffness.
  - Create local submodels to evaluate repairs in key locations.
Statue Restoration

- Local submodels are built parametrically:
  - Boundary conditions taken from full model, so they are equivalent to the same region taken from the full model.
  - Can change the bonded connection to various conditions:
    - Pinned only, with one or two pins of various materials, in various locations and orientations.
    - Adhesive only.
    - Pins and adhesive.
Some general findings:

- Pinning has been used in different forms for centuries (large iron pins), with strong adhesives being a much more recent technology.
- Pinning requires drilling into the marble and is more destructive.
- If pins are used, FE modeling can help optimize the size and location.
- Pins tend to localize the stresses, which is never good especially for brittle materials.
- Pins provide an excellent approach for aligning the parts especially during initial reconstruction and curing of adhesives.
Statue Restoration

- Also performed various analyses to review the load distribution changes that could occur if adhesive bonding would fail at different joints.
Statue Restoration

- Animating the deflection of cases 1 and 2 shows the relative movement in above and below the left knee.
The analysis project concluded that based on strength and creep behavior of the current adhesives, it theoretically is all that would be required to reattach and support the statue.

The actual restoration, which is being done at the Met, is being done based on the input of many experts in various disciplines.

- The most likely scenario may be to use a single pin (for alignment and as a safety) along with adhesive.
- The additional support from the pin is thought to out-weigh the harm of including it.
- The Met plans to show the restored statue along with a display describing the restoration process in 2012 or 2013.