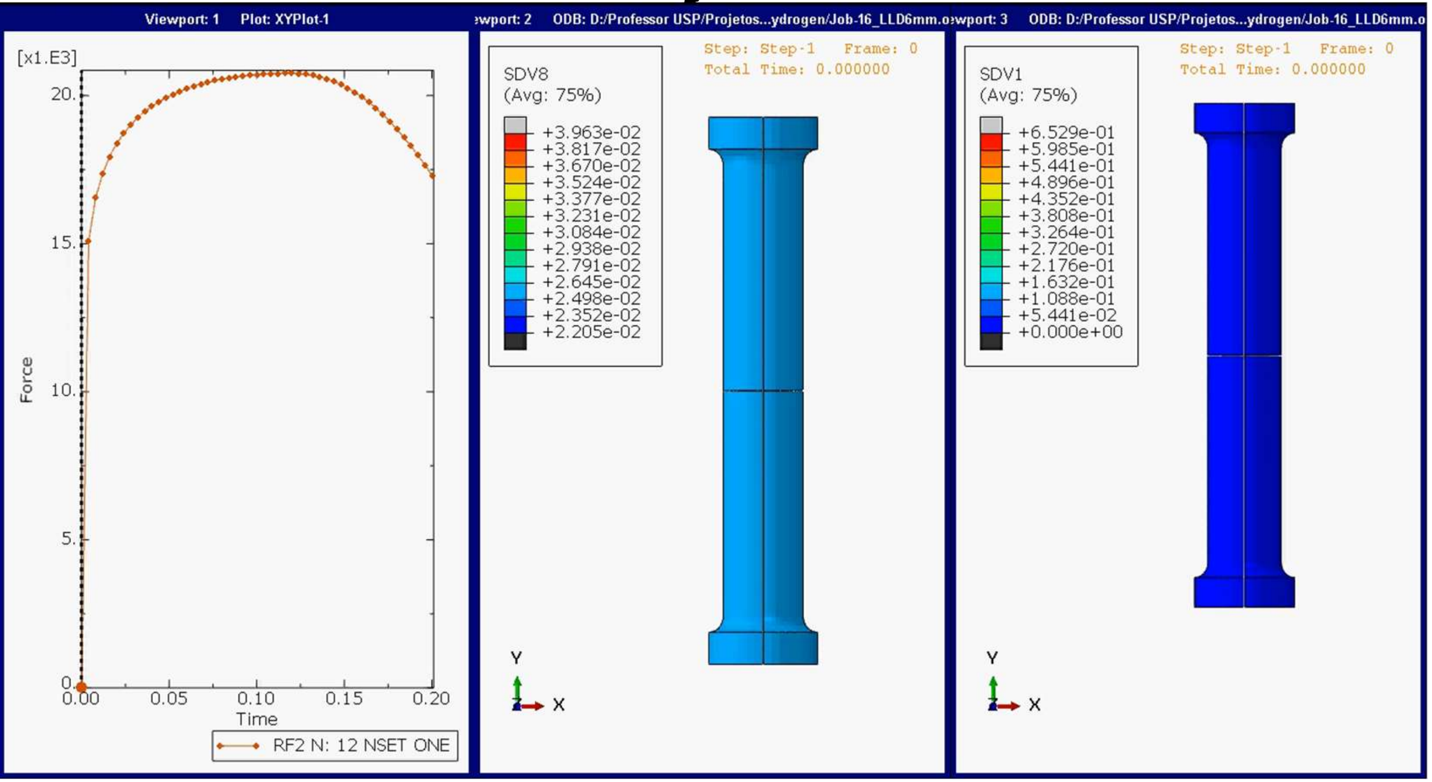
PNV3412- Mecânica de Estruturas Navais e Oceânicas II

Introdução ao método de elementos finitos



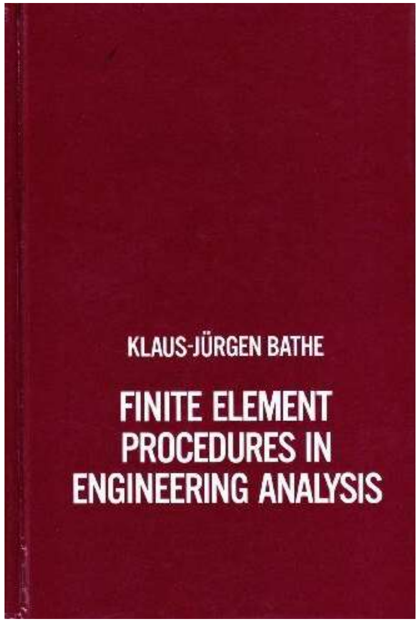
2023

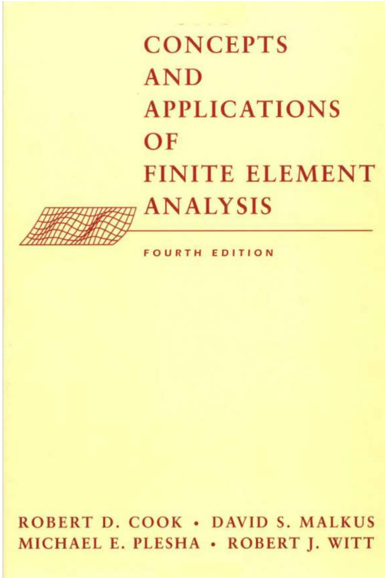
Agenda

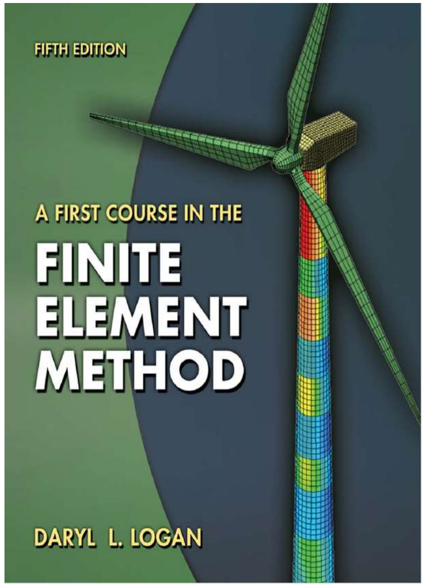
1. Introdução
   i. Motivação
   ii. Aplicações
   iii. Vantagens/desvantagens
2. Método de elementos finitos para problemas 1D
   i. Elementos Barra
   ii. Elementos Viga
3. Método de elementos finitos para problemas 2D
   i. Elementos de Placa
4. Elementos isoparamétricos
   1. Elemento triangular
   2. Elemento quadrilateral
   3. Integração: Quadratura de Gauss
5. Uso do Software Abaqus
6. Projeto Estrutural do Navio/Plataforma
   i. Escantilhão da seção resistente segundo regras de sociedades classificadoras
   ii. Verificação usando MEF/Abaqus

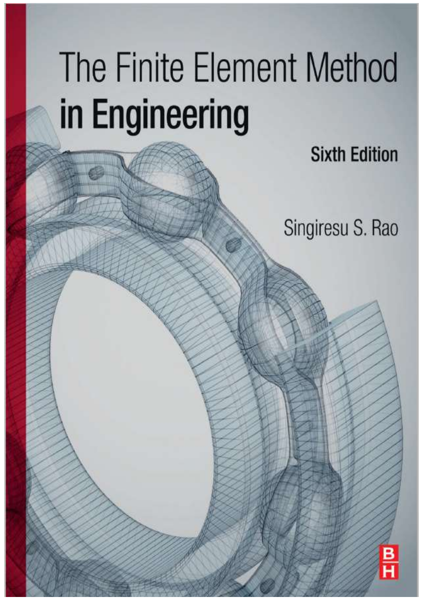
Referências

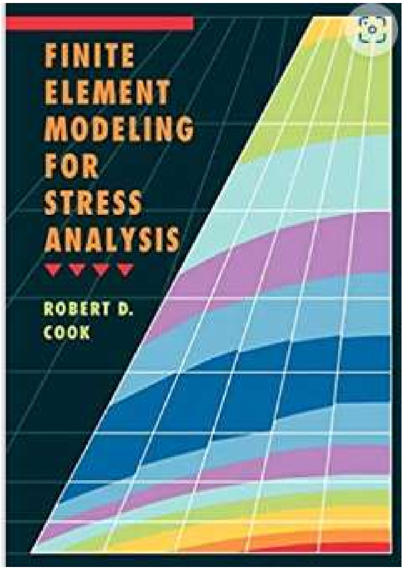
- Bathe, Klaus,Finite element procedures, Prentice Hall.
- Rao, The finite element method in engineering,Butterworth-Heinemann.
- Cook, R. Finite element modeling for stress analysis, John Wiley& Sons.
- Cook, R. Concepts and applications of finite element analysis , John Wiley& Sons.
- Mendoça, Paulo, O método de elementos finitos aplicados à mecânica dos sólidos, Orsa Maggiore, 2019.
- Soriano, Humberto. Método de elementos finitos em análise de estruturas, edUSP.
- Logan, Daryl, A first course in the finite element method, Cengage Learning.
- American Bureau of Shipping, Buckling and Ultimate Strength Assessment for Offshore Structures, 2004.
- Det Norske Veritas, Design of Offshore Steel Structures, General (LRFD Methos), DNV-OS-C101, 2011.

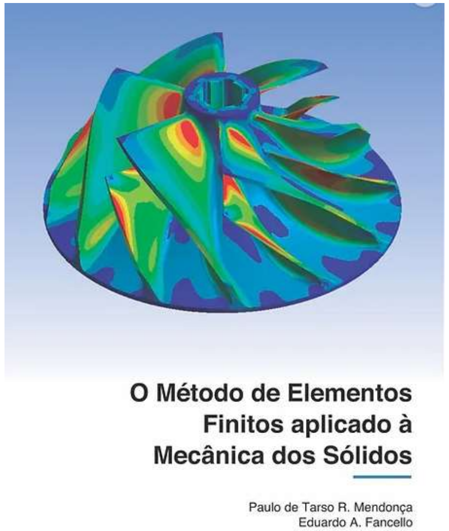

KLAUS-JÜRGEN BATHE
FINITE ELEMENT PROCEDURES IN ENGINEERING ANALYSIS

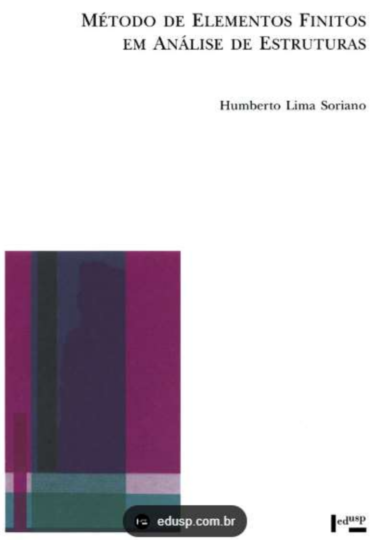

CONCEPTS AND APPLICATIONS OF FINITE ELEMENT ANALYSIS
FOURTH EDITION
ROBERT D. COOK • DAVID S. MALKUS
MICHAEL E. PLESHA • ROBERT J. WITT


FIFTH EDITION
A FIRST COURSE IN THE
FINITE ELEMENT METHOD
DARYL L. LOGAN


The Finite Element Method in Engineering
Sixth Edition
Singiresu S. Rao
B H


FINITE ELEMENT MODELING FOR STRESS ANALYSIS
ROBERT D. COOK


O Método de Elementos Finitos aplicado à Mecânica dos Sólidos
Paulo de Tarso R. Mendonça
Eduardo A. Fancello


Método de Elementos Finitos em Análise de Estruturas
Humberto Lima Soriano
edusp.com.br
edusp


DNV
OFFSHORE STANDARD
DNV-OS-C101
DESIGN OF OFFSHORE STEEL STRUCTURES, GENERAL (LRFD METHOD)
APRIL 2004
Det Norske Veritas

Programação aulas/provas

20 – 24 março de 2023

1. Introdução
   i. Motivação
   ii. Aplicações
   iii. Vantagens/desvantagens

27/ março - 20/abril

2. Método de elementos finitos para problemas 1D
   i. Elementos Barra
   ii. Elementos Viga

24/ março - 04/maio

3. Método de elementos finitos para problemas 2D
   i. Elementos de Placa

P1 -09-05-2023

11/ maio - 06/junho

4. Elementos isoparamétricos
   1. Elemento triangular
   2. Elemento quadrilateral
   3. Integração: Quadratura de Gauss

Ao longo do semestre

5. Uso do Software Abaqus

7/junho – 13/ junho – 15/junho não haverá aula

12/ junho - 30/junho

6. Projeto Estrutural do Navio/Plataforma
   i. Escantilhão da seção resistente segundo regras de sociedades classificadoras (ABS/DNV/BV)
   ii. Modelagem e Verificação usando MEF/Abaqus

P2 -27-06-2023

Perímetro da circunferência

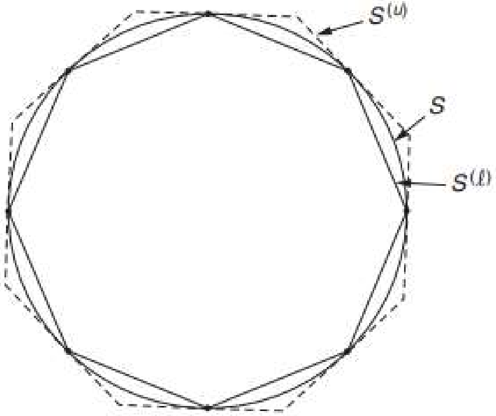


FIGURE 1.3 Lower and upper bounds to the circumference of a circle.

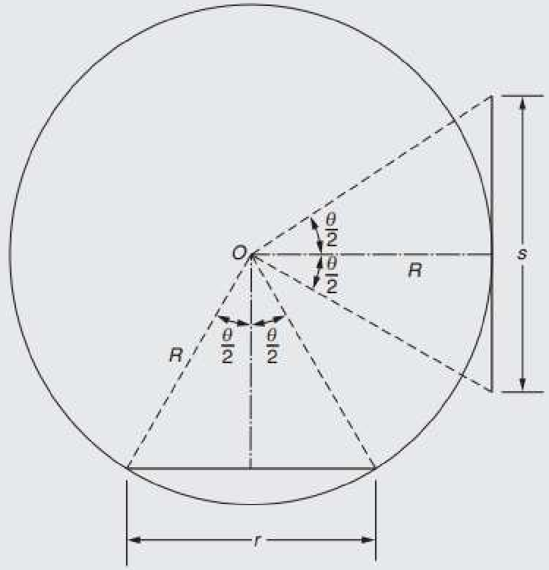


FIGURE 1.4 Sides of inscribed and circumscribed polygons.

$$r = 2R\sin\frac{\pi}{n}, \quad s = 2R\tan\frac{\pi}{n}$$

Thus, the perimeters of the inscribed and circumscribed polygons are given by

$$S^{(l)} = nr = 2nR\sin\frac{\pi}{n}, \quad S^{(u)} = ns = 2nR\tan\frac{\pi}{n}$$

which can be rewritten as

$$S^{(l)} = 2\pi R\left[\frac{\sin\frac{\pi}{n}}{\frac{\pi}{n}}\right], \quad S^{(u)} = 2\pi R\left[\frac{\tan\frac{\pi}{n}}{\frac{\pi}{n}}\right]$$

As $n \to \infty, \frac{\pi}{n} \to 0$, and hence

$$S^{(l)} \to 2\pi R = S, \quad S^{(u)} \to 2\pi R = S$$

Responsabilidade do usuário

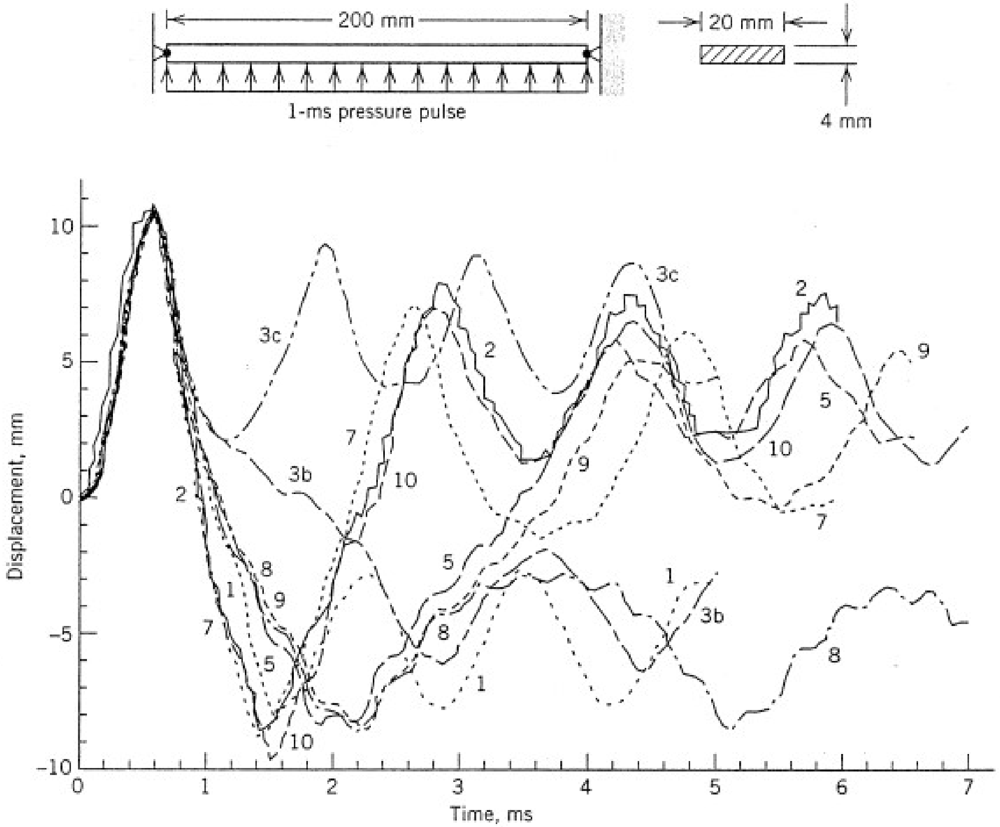


Fig. 1.5-1. Lateral midpoint displacement versus time for a beam loaded by a pressure pulse [1.6] The material is elastic–perfectly plastic. Plots were generated by various users and various codes.

polish of their presentation. But smooth and colorful stress contours can be produced by *any* model, good or bad. It is possible that most FE analyses are so flawed that they cannot be trusted. Even a poor mesh, inappropriate element types, incorrect loads, or improper supports may produce results that appear reasonable on casual inspection. A poor model may have defects that are not removed by refinement of the mesh.

Finite Element Modeling for Stress Analysis

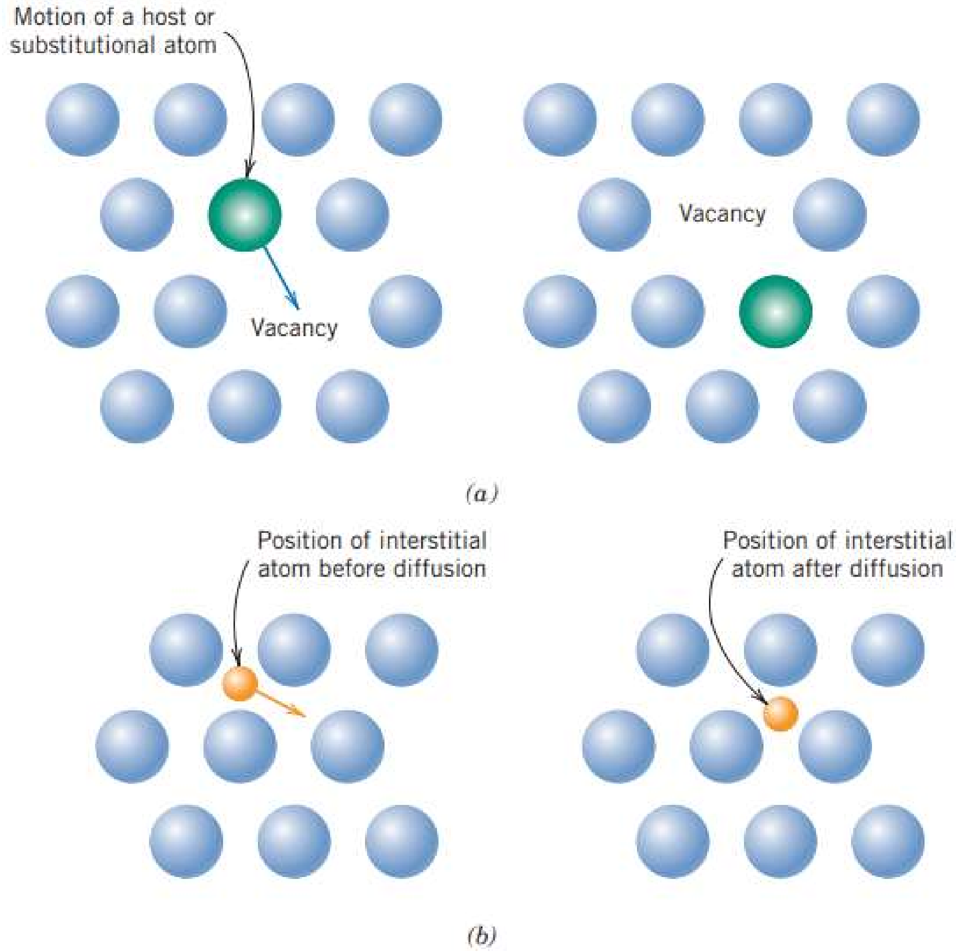
Robert D. Cook
University of Wisconsin - Madison

TABLE 1.1 Engineering Applications of the Finite Element Method

Area of Study	Equilibrium Problems	Eigenvalue Problems	Propagation Problems
1. Civil engineering structures	Static analysis of trusses, frames, folded plates, shell roofs, shear walls, bridges, and prestressed concrete structures	Natural frequencies and modes of structures; stability of structures	Propagation of stress waves; response of structures to aperiodic loads
2. Aircraft structures	Static analysis of aircraft wings, fuselages, fins, rockets, spacecraft, and missile structures	Natural frequencies, flutter, and stability of aircraft, rocket, spacecraft, and missile structures	Response of aircraft structures to random loads, and dynamic response of aircraft and spacecraft to aperiodic loads
3. Heat conduction	Steady-state temperature distribution in solids and fluids	—	Transient heat flow in rocket nozzles, internal combustion engines, turbine blades, fins, and building structures
4. Geomechanics	Analysis of excavations, retaining walls, underground openings, rock joints, and soil–structure interaction problems; stress analysis in soils, dams, layered piles, and machine foundations	Natural frequencies and modes of dam–reservoir systems and soil–structure interaction problems	Time-dependent soil–structure interaction problems; transient seepage in soils and rocks; stress wave propagation in soils and rocks
5. Hydraulic and water resources engineering; hydrodynamics	Analysis of potential flows, free surface flows, boundary layer flows, viscous flows, transonic aerodynamic problems; analysis of hydraulic structures and dams	Natural periods and modes of shallow basins, lakes, and harbors; sloshing of liquids in rigid and flexible containers	Analysis of unsteady fluid flow and wave propagation problems; transient seepage in aquifers and porous media; rarefied gas dynamics; magnetohydrodynamic flows
6. Nuclear engineering	Analysis of nuclear pressure vessels and containment structures; steady-state temperature distribution in reactor components	Natural frequencies and stability of containment structures; neutron flux distribution	Response of reactor containment structures to dynamic loads; unsteady temperature distribution in reactor components; thermal and viscoelastic analysis of reactor structures
7. Biomedical engineering	Stress analysis of eyeballs, bones, and teeth; load-bearing capacity of implant and prosthetic systems; mechanics of heart valves	—	Impact analysis of skull; dynamics of anatomical structures
8. Mechanical design	Stress concentration problems; stress analysis of pressure vessels, pistons, composite materials, linkages, and gears	Natural frequencies and stability of linkages, gears, and machine tools	Crack and fracture problems under dynamic loads
9. Electrical machines and electromagnetics	Steady-state analysis of synchronous and induction machines, eddy current, and core losses in electric machines, magnetostatics	—	Transient behavior of electromechanical devices such as motors and actuators, magnetodynamics

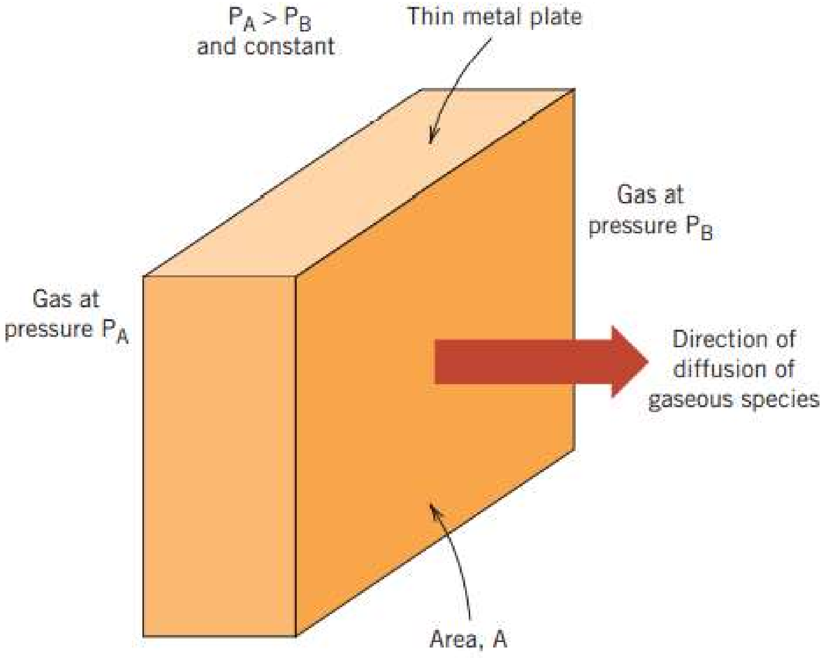
Difusão atômica em sólidos

Figure 5.3 Schematic representations of (a) vacancy diffusion and (b) interstitial diffusion.

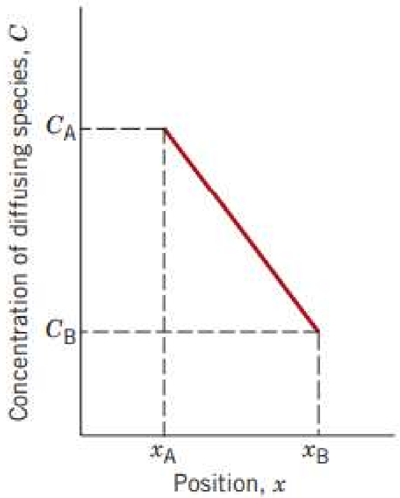



The hydrogen-induced cracking failure of an API 5L X60 line pipe.

Difusão atômica em sólidos



(a)



(b)

Fick's first law—
diffusion flux for
steady-state diffusion
(in one direction)

$$J = -D\frac{\partial C}{\partial x}$$

Fick's second law—
diffusion equation
for nonsteady-state
diffusion (in one
direction)

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

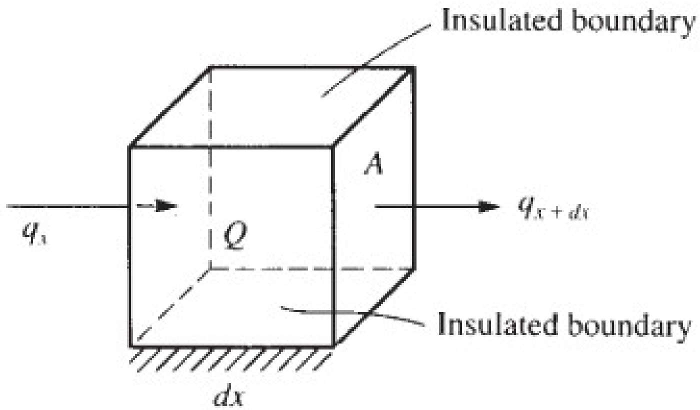
Transferência de calor

$$E_{in} + E_{generated} = \Delta U + E_{out}$$

Fourier's law of heat conduction

equivalente

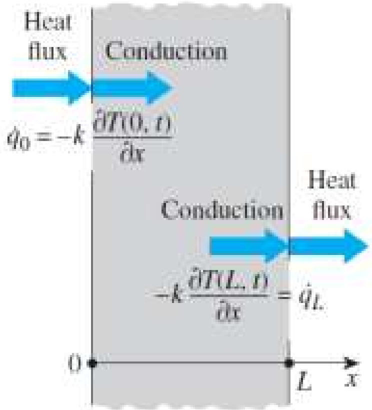
$$q_x = -K_{xx}\frac{dT}{dx} \quad \equiv \quad \sigma_x = E\frac{du}{dx}$$



heat conduction equation

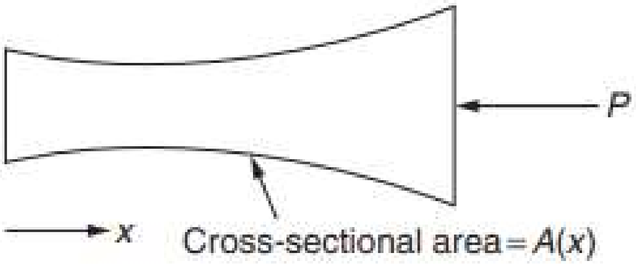
$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial T}{\partial x}\right) + Q = \rho c\frac{\partial T}{\partial t}$$

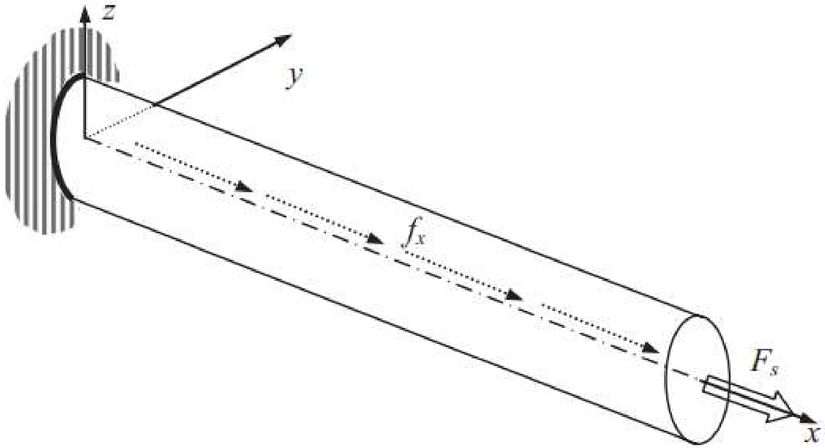
Q is the internal heat source



$$K_{xx}\frac{\partial^2 T}{\partial x^2} = \rho c\frac{\partial T}{\partial t}$$

Barra sob Carga Axial





Dynamic equilibrium equations

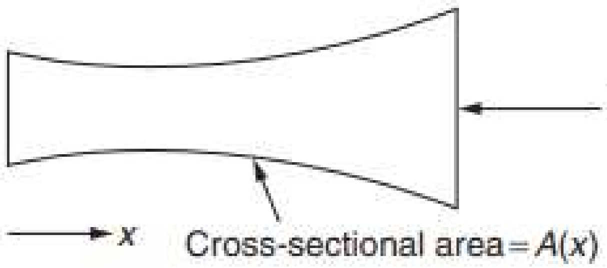
$$\frac{\partial \sigma_x}{\partial x} + b_x = \rho \frac{d^2 u}{dt^2} \longleftarrow \sigma_x = E \frac{du}{dx}$$

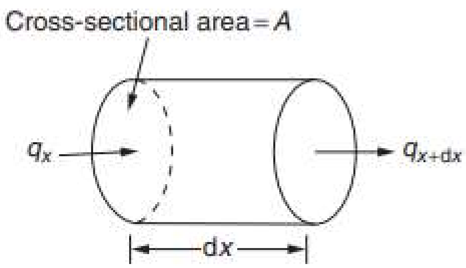
$$E \frac{\partial^2 u}{\partial x^2} + b_x = \rho \frac{d^2 u}{dt^2}$$

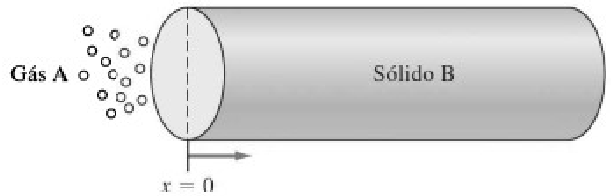
Static Equilibrium

$$E \frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Problemas de engenharia (1D)







$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

$$K_{xx}\frac{\partial^2 T}{\partial x^2} + Q = 0$$

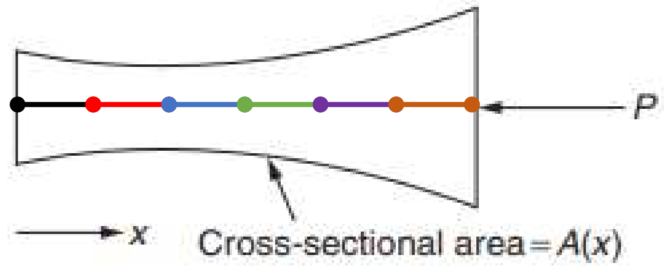
$$D\frac{\partial^2 C}{\partial x^2} + q = 0$$

Equação de Poisson

Formulação e solução do problema

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson

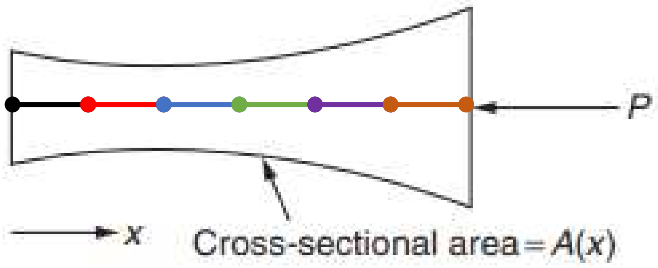


1. Discretização da região onde a solução é buscada em um número finito de sub-regiões (elementos).
2. Aproximação da solução em cada elemento utilizando interpolação polinomial
3. **Obtenção** das equações correspondentes a cada elemento.
4. Montagem de um sistema global que inclui as equações de todos os elementos.
5. Resolução do sistema de equações resultante de forma a obter a solução do problema.

Problemas de engenharia (1D)

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson



1 Assumir um campo de deslocamentos

$$u_e(x) = \begin{bmatrix} 1 & x & x^2 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}$$

Função aproximação de 2 grau

ou

$$u_e(x) = \begin{bmatrix} 1 & x \end{bmatrix} \begin{bmatrix} \alpha_1 \\ 2 \end{bmatrix}$$

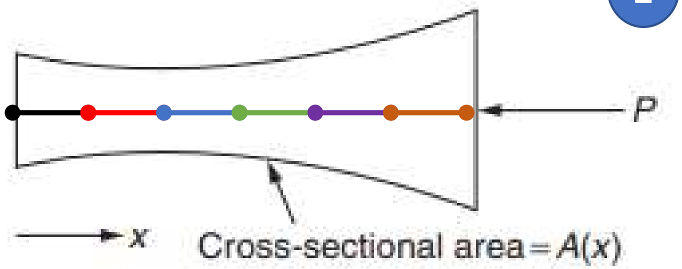
Função aproximação de 1 grau

- ✓ Escolher o grau do polinômio segundo a quantidade de deslocamentos nodais do elemento!
- ✓ Número de parâmetros desconhecidos do polinômio de aproximação seja igual aos deslocamentos nodais do elemento (graus de liberdade do elemento)!

Problemas de engenharia (1D)

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson



2 Derivar a formulação da matriz rigidez K do elemento e o vetor de carga R

Ku=R

- ✓ Formulação fraca do problema.
- ✓ A formulação pode ser obtida por:
  - ✓ Princípio Variacional
    - ✓ Trabalhos virtuais
    - ✓ Mínima energia potencial
  - ✓ Método dos resíduos ponderados (geral)
    - ✓ Galerkin
    - ✓ Least square/Mínimos quadrados
  - ✓ Equilíbrio (casos simples)

energia potencial

$$\pi = U - W \qquad U = \int_V \frac{1}{2}\sigma\varepsilon dV \qquad W = Pu$$

$$\sigma = E\frac{du}{dx} \leftarrow \sigma = E\varepsilon \leftarrow \varepsilon = \frac{du}{dx}$$

$$U = \int_V \frac{1}{2}E\left(\frac{du}{dx}\right)^2 dV$$

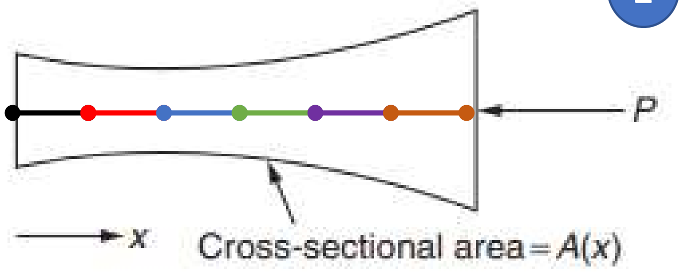
$$u_e(x) = \alpha_1 + \alpha_2 x$$

α_1, α_2 Constantes podem ser definidas em termos dos deslocamentos nodais do elemento

Problemas de engenharia (1D)

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson



2 Derivar a formulação da matriz rigidez K e o vetor de carga R do elemento **e**

energia potencial $\pi = U - W$

$$U = \frac{AE}{2}\int_0^l \left(\frac{du}{dx}\right)^2 dx \qquad W = Pu$$

$$u_e(x) = \alpha_1 + \alpha_2 x \quad \rightarrow \quad u_e(x) = u_1^e + \left(\frac{u_2^e - u_1^e}{l^e}\right)x \rightarrow \quad \frac{du_e(x)}{dx} = \varepsilon^e = \left(\frac{u_2^e - u_1^e}{l^e}\right)$$

$$u_e(x=0) = \alpha_1 + \alpha_2 x = u_1^i \rightarrow \alpha_1 = u_1^e$$

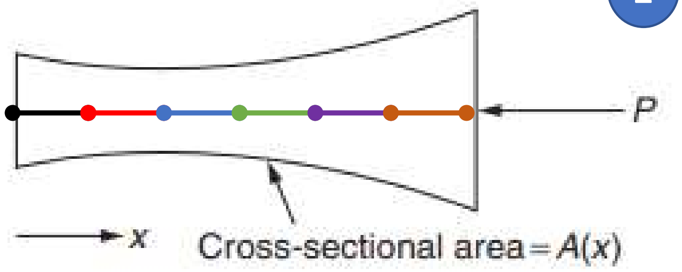
$$u_e(x=l^e) = \alpha_1 + \alpha_2 l^e = u_2^e \rightarrow \alpha_2 = \frac{u_2^e - u_1^{e\,i}}{l^e}{}_1$$

$$\boxed{U^e = \frac{A^e E^e}{2}\int_0^{l^e} \left(\frac{u_2^e - u_1^e}{l^e}\right)^2 dx}$$

Problemas de engenharia (1D)

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson



2 Derivar a formulação da matriz rigidez K e o vetor de carga R do elemento **e**

energia potencial $\pi = U - W$

$$\boxed{U^e = \frac{A^e E^e}{2}\int_0^{l^e}\left(\frac{u_2^e - u_1^e}{l^e}\right)^2 dx}$$

$$W = Pu$$

$$U^e = \frac{A^e E^e}{2{l_e}^2}\int_o^{l^e}(u_2^e)^2 - 2u_2^e u_1^e + (u_2^e)^2\, dx \rightarrow$$

$$U^e = \frac{A^e E^e}{2l_e}\left[(u_2^e)^2 - 2u_2^e u_1^e + (u_2^e)^2\right]$$

$$|||$$

$$U^e = \frac{1}{2}[\vec{u}_e]^T[K^e]\,[\vec{u}_e]$$ Representação matricial

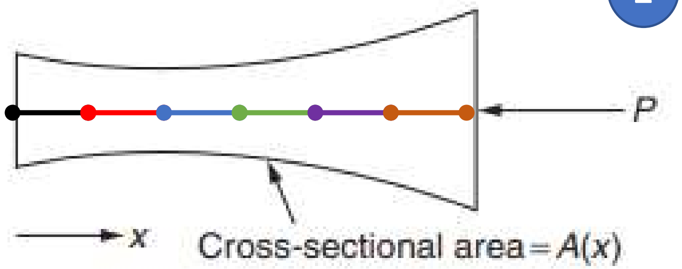
$$[\vec{u}_e] = \begin{bmatrix} u_1^e \\ u_2^e \end{bmatrix} \qquad [K^e] = \frac{A^e E^e}{l_e}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$

Matriz Simétrica em problemas estruturais

Problemas de engenharia (1D)

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson



2 Derivar a formulação da matriz rigidez K e o vetor de carga R do elemento **e**

energia potencial $\pi = U - W$

$$\boxed{U^e = \frac{1}{2}[\vec{u}_e]^T[K^e]\,[\vec{u}_e]}$$

$$W = P_i u_i$$

Mínima energia potencial: $$\frac{\partial \pi}{\partial u_i} = 0, i = 1,2,3,..n$$

$$\frac{\partial \pi}{\partial u_i} = \frac{\partial}{\partial u_i}\left(\frac{1}{2}[\vec{u}_e]^T[K^e]\,[\vec{u}_e] - P_i u_i^e\right)$$

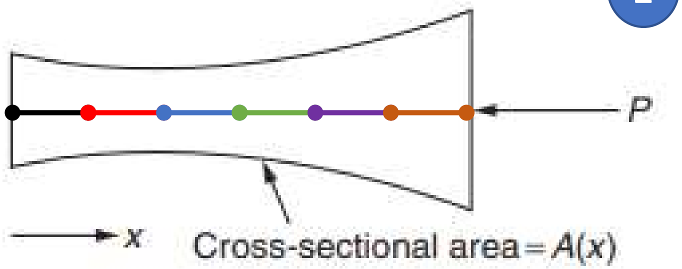
Para um (1) elemento

$$\frac{\partial \pi}{\partial u_i} = [K^e]\,[\vec{u}_e] - P_i = 0$$

Problemas de engenharia (1D)

$$E\frac{\partial^2 u}{\partial x^2} + b_x = 0$$

Equação de Poisson



2 Derivar a formulação da matriz rigidez K e o vetor de carga R do elemento **e**

$$[K^e] = \frac{A^e E^e}{l_e}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \qquad [P^e] = [R^e] = \begin{bmatrix} P_1 \\ P_2 \end{bmatrix}$$

3 Montar a matriz rigidez e o vetor de carga do sistema (global) e obter o sistema de equações

$$[\bar{K}] = \sum_e K^e$$

$$[\bar{K}]\,[\vec{u}] - \vec{P} = 0$$

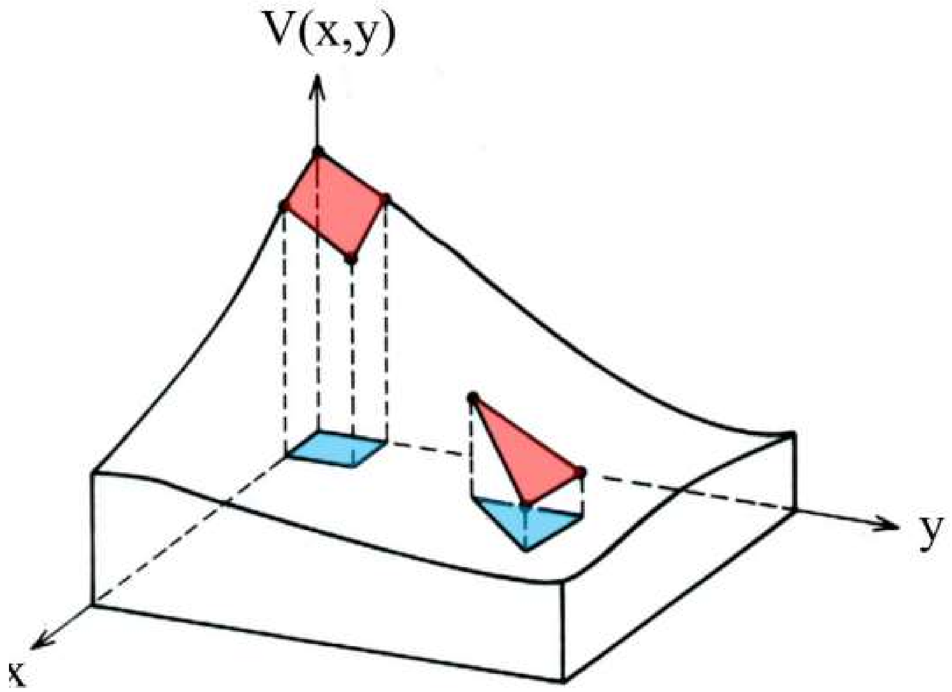
$$[\vec{P}] = \sum_e P^e$$

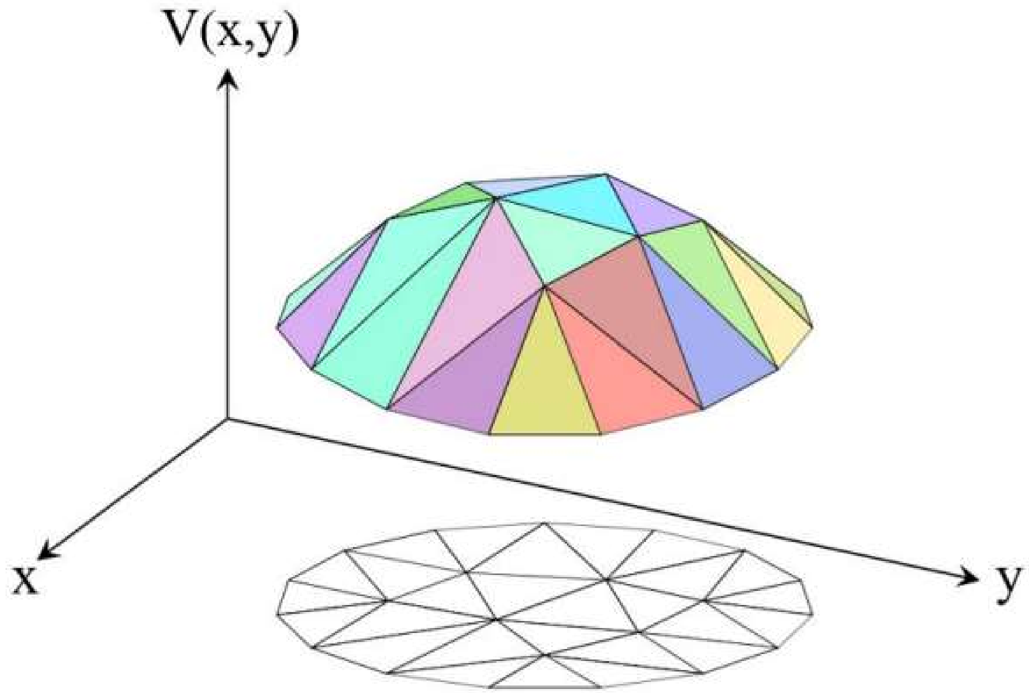
4 Incorporar as condições de contorno e resolver o sistema de equações

$$[\vec{u}] = [\bar{K}]^{-1}\vec{P}$$

Aproximação de uma função escalar bidimensional V(x,y)

- Usando elementos (triangulares ou quadrangulares) de **primeira ordem**





Domínio de cálculo = plano xy

EXAMPLES OF FEM

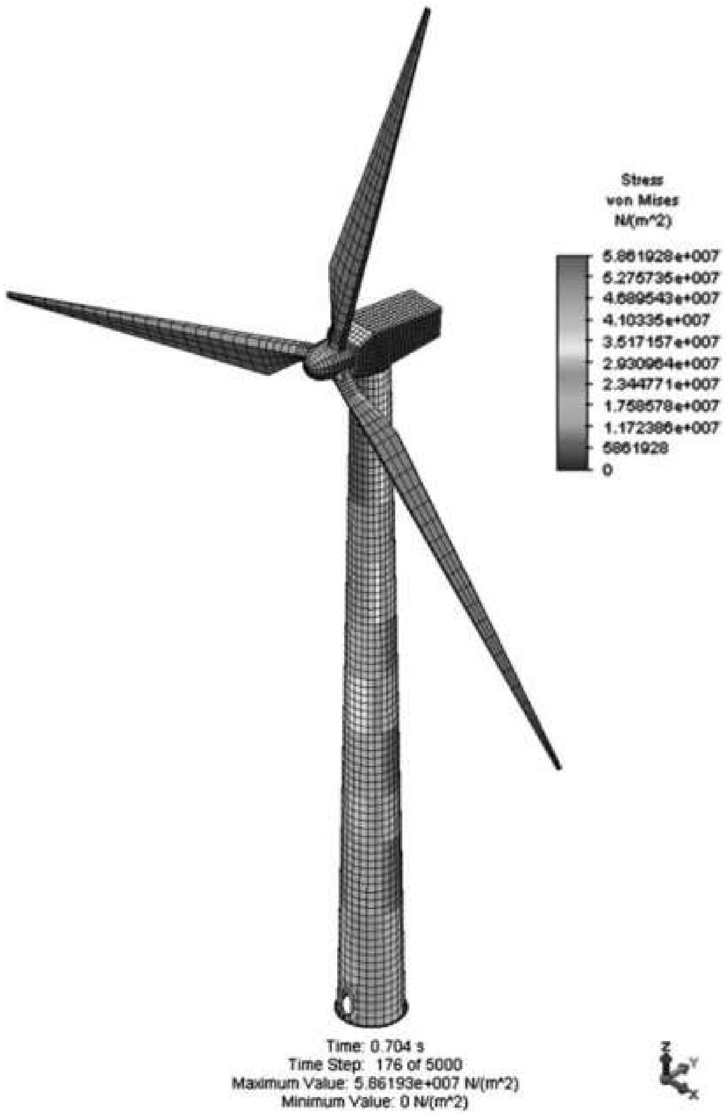


Figure 1–12 Finite element model showing the von Mises stress plot of a wind mill tower at a critical time step using a nonlinear finite element simulation (Courtesy of Valmont West Coast Engineering)

EXAMPLES OF FEM

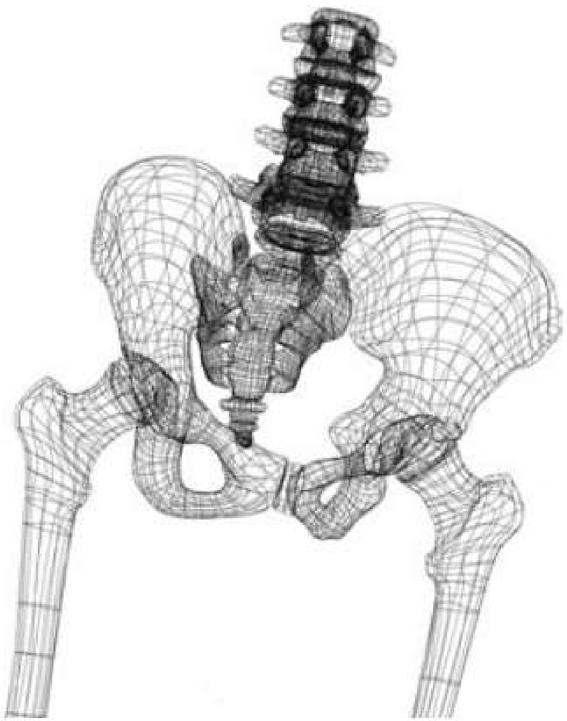


Figure 1–9 Finite element model of a human pelvis (Studio MacBeth/Science Photo Library)

EXAMPLES OF FEM

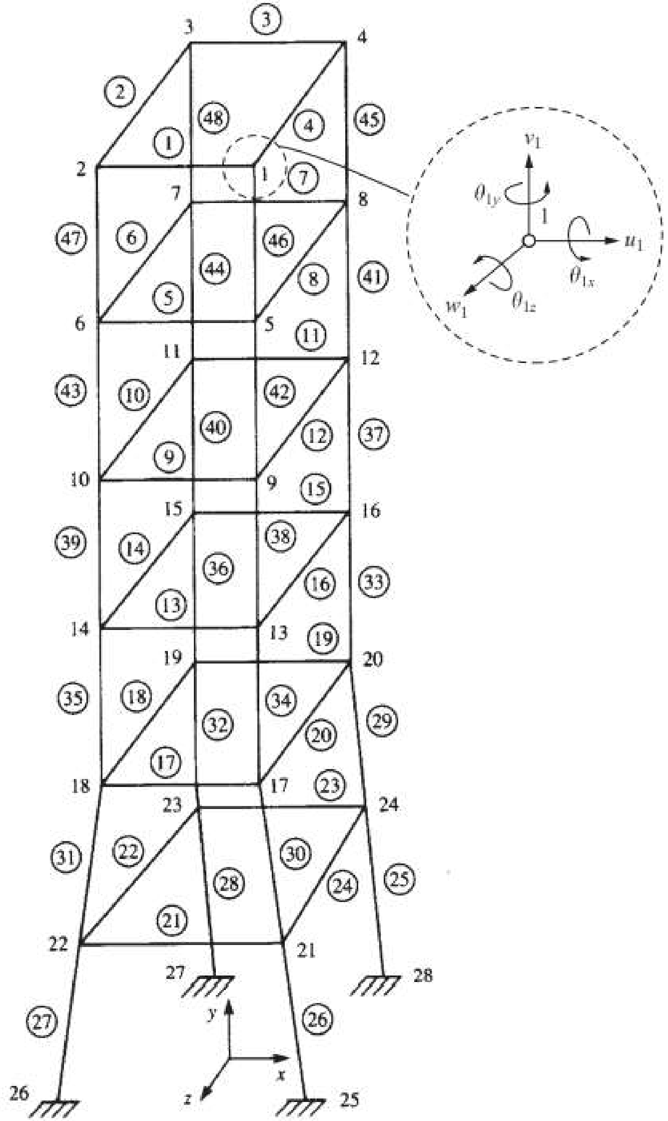


Figure 1–2 Discretized railroad control tower (28 nodes, 48 beam elements) with typical degrees of freedom shown at node 1, for example (By Daryl L. Logan)

EXAMPLES OF FEM

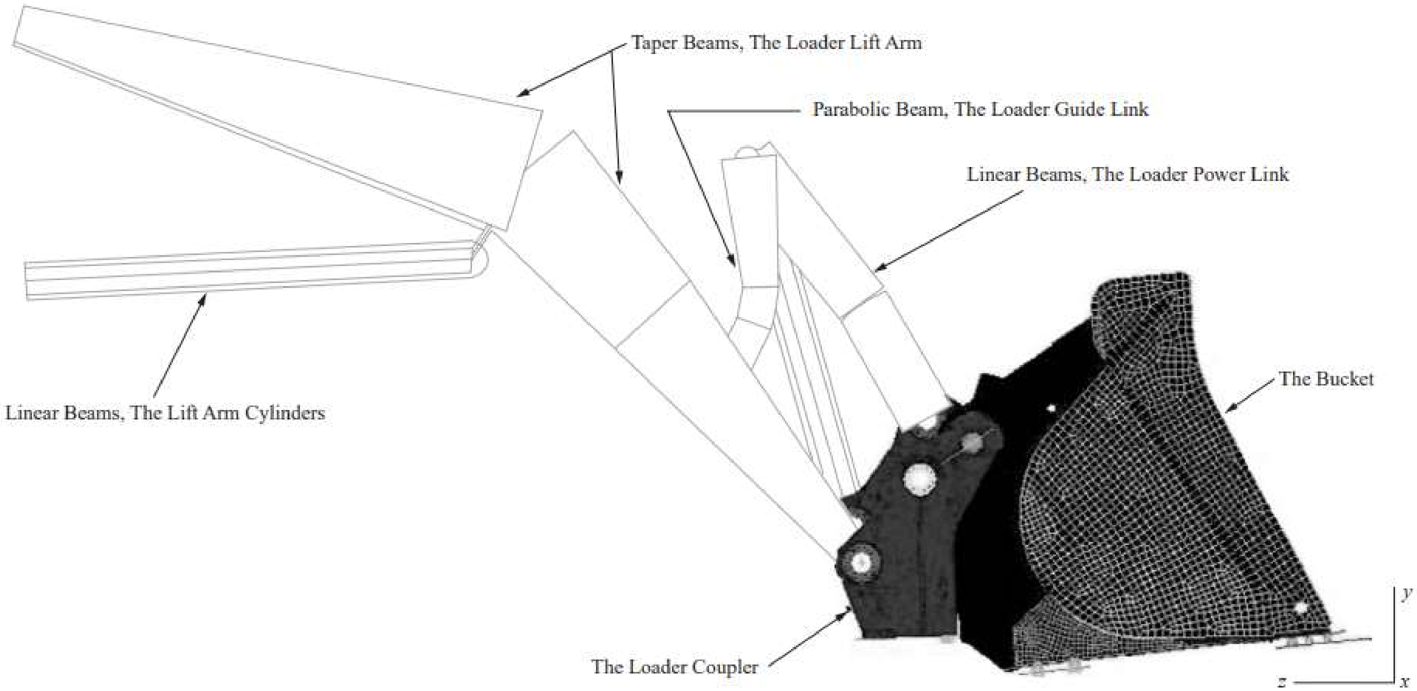
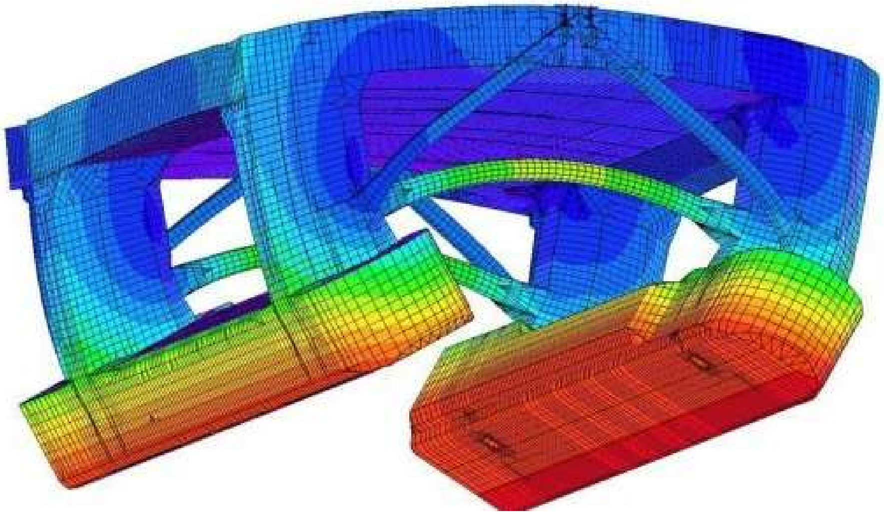
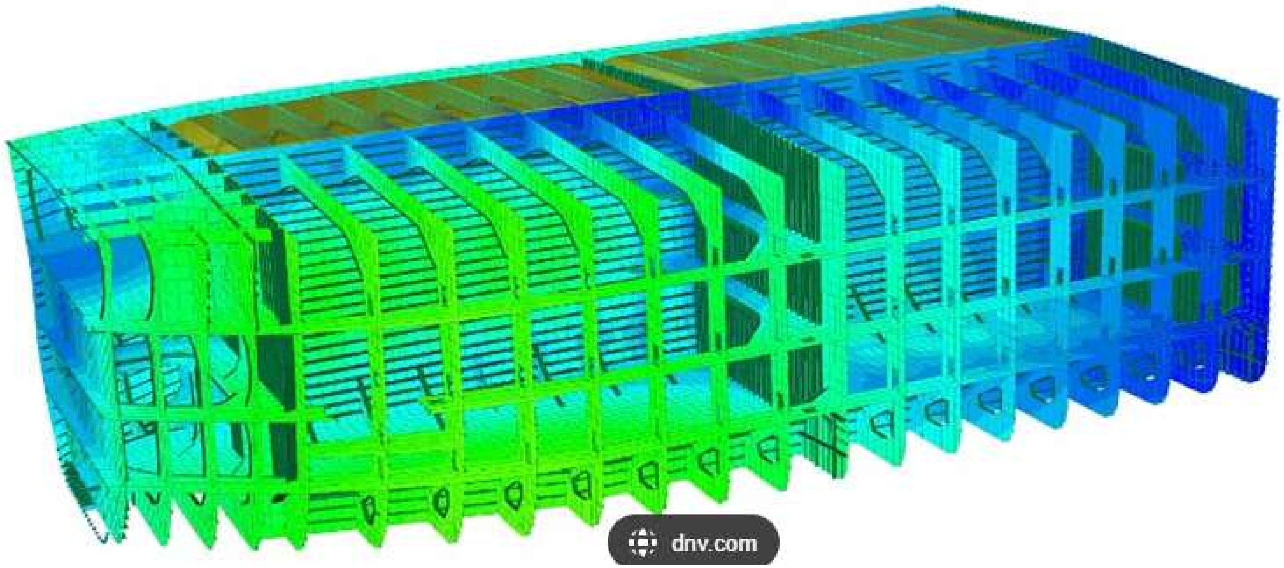


Figure 1–10 Finite element model of a 710G bucket with 169,595 elements and 185,026 nodes used (including 78,566 thin-shell linear quadrilateral elements for the bucket and coupler, 83,104 solid linear brick elements to model the bosses, and 212 beam elements to model lift arms, lift arm cylinders, and guide links) (Courtesy of Yousif Omer, Structural Design Engineer, Construction and Forestry Division, John Deere Dubuque Works)

EXAMPLES OF FEM





EXAMPLES OF FEM