

Pearson International Edition

FINITE ELEMENT ANALYSIS

Theory and Application with ANSYS

THIRD EDITION

Saeed Moaveni

Contents

Preface xi

Acknowledgments xv

1 Introduction 1

- 1.1** Engineering Problems 2
- 1.2** Numerical Methods 5
- 1.3** A Brief History of the Finite Element Method and ANSYS 6
- 1.4** Basic Steps in the Finite Element Method 6
- 1.5** Direct Formulation 8
- 1.6** Minimum Total Potential Energy Formulation 37
- 1.7** Weighted Residual Formulations 43
- 1.8** Verification of Results 48
- 1.9** Understanding the Problem 49
 - Summary 53
 - References 54
 - Problems 54

2 Matrix Algebra 66

- 2.1** Basic Definitions 66
- 2.2** Matrix Addition or Subtraction 69
- 2.3** Matrix Multiplication 69
- 2.4** Partitioning of a Matrix 73
- 2.5** Transpose of a Matrix 77
- 2.6** Determinant of a Matrix 81
- 2.7** Solutions of Simultaneous Linear Equations 86
- 2.8** Inverse of a Matrix 94
- 2.9** Eigenvalues and Eigenvectors 98
- 2.10** Using MATLAB to Manipulate Matrices 102
- 2.11** Using Excel to Manipulate Matrices 106
 - Summary 112
 - References 113
 - Problems 113

3 Trusses 117

- 3.1** Definition of a Truss 117
- 3.2** Finite Element Formulation 118
- 3.3** Space Trusses 135

3.4	Overview of the ANSYS Program	137
3.5	Examples Using ANSYS	144
3.6	Verification of Results	177
	Summary	179
	References	179
	Problems	179
4	Axial Members, Beams, and Frames	189
4.1	Members Under Axial Loading	189
4.2	Beams	197
4.3	Finite Element Formulation of Beams	202
4.4	Finite Element Formulation of Frames	213
4.5	Three-Dimensional Beam Element	219
4.6	An Example Using ANSYS	222
4.7	Verification of Results	236
	Summary	238
	References	239
	Problems	240
5	One-Dimensional Elements	252
5.1	Linear Elements	252
5.2	Quadratic Elements	256
5.3	Cubic Elements	258
5.4	Global, Local, and Natural Coordinates	261
5.5	Isoparametric Elements	263
5.6	Numerical Integration: Gauss-Legendre Quadrature	265
5.7	Examples of One-Dimensional Elements in ANSYS	270
	Summary	270
	References	270
	Problems	270
6	Analysis of One-Dimensional Problems	277
6.1	Heat Transfer Problems	277
6.2	A Fluid Mechanics Problem	292
6.3	An Example Using ANSYS	296
6.4	Verification of Results	311
	Summary	312
	References	312
	Problems	313
7	Two-Dimensional Elements	316
7.1	Rectangular Elements	316
7.2	Quadratic Quadrilateral Elements	320

7.3	Linear Triangular Elements	325
7.4	Quadratic Triangular Elements	330
7.5	Axisymmetric Elements	334
7.6	Isoparametric Elements	339
7.7	Two-Dimensional Integrals: Gauss-Legendre Quadrature	341
7.8	Examples of Two-Dimensional Elements in ANSYS	344
	Summary	345
	References	345
	Problems	346
8	More ANSYS	353
8.1	ANSYS Program	353
8.2	ANSYS Database and Files	354
8.3	Creating a Finite Element Model with ANSYS: Preprocessing	356
8.4	<i>h</i> -Method Versus <i>p</i> -Method	370
8.5	Applying Boundary Conditions, Loads, and the Solution	370
8.6	Results of Your Finite Element Model: Postprocessing	373
8.7	Selection Options	378
8.8	Graphics Capabilities	379
8.9	Error-Estimation Procedures	381
8.10	An Example Problem	383
	Summary	397
	References	398
9	Analysis of Two-Dimensional Heat Transfer Problems	405
9.1	General Conduction Problems	405
9.2	Formulation with Rectangular Elements	412
9.3	Formulation with Triangular Elements	423
9.4	Axisymmetric Formulation of Three-Dimensional Problems	434
9.5	Unsteady Heat Transfer	442
9.6	Conduction Elements Used by ANSYS	452
9.7	Examples Using ANSYS	453
9.8	Verification of Results	491
	Summary	491
	References	493
	Problems	493
10	Analysis of Two-Dimensional Solid Mechanics Problems	505
10.1	Torsion of Members with Arbitrary Cross-Section Shape	505
10.2	Plane-Stress Formulation	515
10.3	Isoparametric Formulation: Using a Quadrilateral Element	523
10.4	Axisymmetric Formulation	530
10.5	Basic Failure Theories	532

10.6	Examples Using ANSYS	533
10.7	Verification of Results	554
	Summary	554
	References	556
	Problems	556

11 Dynamic Problems 565

11.1	Review of Dynamics	565
11.2	Review of Vibration of Mechanical and Structural Systems	579
11.3	Lagrange's Equations	596
11.4	Finite Element Formulation of Axial Members	598
11.5	Finite Element Formulation of Beams and Frames	602
11.6	Examples Using ANSYS	616
	Summary	636
	References	636
	Problems	636

12 Analysis of Fluid Mechanics Problems 643

12.1	Direct Formulation of Flow Through Pipes	643
12.2	Ideal Fluid Flow	649
12.3	Groundwater Flow	655
12.4	Examples Using ANSYS	658
12.5	Verification of Results	679
	Summary	680
	References	681
	Problems	682

13 Three-Dimensional Elements 687

13.1	The Four-Node Tetrahedral Element	687
13.2	Analysis of Three-Dimensional Solid Problems Using Four-Node Tetrahedral Elements	690
13.3	The Eight-Node Brick Element	695
13.4	The Ten-Node Tetrahedral Element	697
13.5	The Twenty-Node Brick Element	698
13.6	Examples of Three-Dimensional Elements in ANSYS	700
13.7	Basic Solid-Modeling Ideas	704
13.8	A Thermal Example Using ANSYS	715
13.9	A Structural Example Using ANSYS	732
	Summary	745
	References	745
	Problems	745

14 Design and Material Selection 754

- 14.1** Engineering Design Process 755
- 14.2** Material Selection 758
- 14.3** Electrical, Mechanical, and Thermophysical Properties of Materials 759
- 14.4** Common Solid Engineering Materials 761
- 14.5** Some Common Fluid Materials 768
 - Summary 770
 - Reference 770
 - Problems 770

15 Design Optimization 772

- 15.1** Introduction to Design Optimization 772
- 15.2** The Parametric Design Language of ANSYS 776
- 15.3** Examples of Batch Files 778
- 15.4** An Example of an Optimization Batch Files 792
 - Summary 800
 - References 800
 - Problems 800

Appendix A Mechanical Properties of Some Materials 801

Appendix B Thermophysical Properties of Some Materials 804

Appendix C Properties of Common Line and Area Shapes 805

Appendix D Geometric Properties of Structural Steel Shapes 808

Appendix E Conversion Factors 812

Appendix F An Introduction to MATLAB 814

Index 849