

MACHINE DESIGN

An
Integrated
Approach

SIXTH EDITION



Robert L. Norton

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An Integrated Approach

Sixth Edition

Robert L. Norton P.E.

*Milton P. Higgins II
Distinguished Professor
Emeritus*

Worcester Polytechnic Institute

Worcester, Massachusetts



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ABOUT THE AUTHOR

Robert L. Norton earned undergraduate degrees in both mechanical engineering and industrial technology at Northeastern University, an MS in engineering design at Tufts University, and was awarded a Doctor of Engineering (h.c.) by Worcester Polytechnic Institute (WPI). He is a registered professional engineer in Massachusetts and Florida. He has over 50 years experience in engineering design and manufacturing and over 40 years experience teaching mechanical engineering, engineering design, computer science, and related subjects at Northeastern University, Tufts University, and WPI. Norton has been on the faculty of WPI since 1981, and is currently the Milton P. Higgins II Distinguished Professor Emeritus. He is also the founder and president of Norton Associates Engineering Consultants since 1970.

At Polaroid Corporation for 10 years, he designed cameras, related mechanisms, and high-speed automated machinery. He spent three years at Jet Spray Cooler Inc., designing food-handling machinery and products. For five years he helped develop artificial-heart and noninvasive assisted-circulation devices at the Tufts New England Medical Center and Boston City Hospital. Since leaving industry to join academia in 1974, he has continued as an independent consultant on engineering projects ranging from disposable medical products to high-speed production machinery. He holds thirteen U.S. patents.

He is the author of numerous technical papers and journal articles covering kinematics, dynamics of machinery, cam design and manufacturing, computers in education, engineering education, and of the texts *Design of Machinery*, *Kinematics and Dynamics of Machinery*, *Machine Design: An Integrated Approach*, and the *Cam Design and Manufacturing Handbook*. He is a Life Fellow of the American Society of Mechanical Engineers and a past member of the Society of Automotive Engineers and the American Society for Engineering Education. In 2007, he was selected as a U.S. Professor of the Year by the Council for the Advancement and Support of Education (CASE) and the Carnegie Foundation for the Advancement of Teaching, who jointly present the only national awards for higher-education teaching excellence given in the United States of America.

WHAT USERS SAY ABOUT THE BOOK

Your text is the best of all the texts I have used—the balance of fundamentals and practice is especially important, and you have achieved that with aplomb!

—Professor John P. H. Steele, *Colorado School of Mines*

This book is one of the best-written on any engineering subject that I have come across. We switched to the book because we felt that the students would get a lot out of reading the text.

—Professor Ed Howard, *Milwaukee School of Engineering*

(The) writing is clear and meaningful, (and the) text is much more accessible to students because of the practical nature of (its) case studies and problem sets.

—Professor Douglas Walcerz, *York College of Pennsylvania*

I'm doing my machine design homework now, and . . . your book is the single best text I have ever used in my educational career. It is straightforward, easy to understand and has good examples.

—Josh, student, *Colorado School of Mines*

This book is dedicated to the memory of:

Donald N. Zwiep

1924–2012

Provost, Department Head, and Professor Emeritus
Worcester Polytechnic Institute

*A gentleman and a leader,
without whose faith and foresight,
this book would never have been written.*

PREFACE

Introduction

This text is intended for the *Design of Machine Elements* courses typically given in the junior year of most mechanical engineering curricula. The usual prerequisites are a first course in *Statics and Dynamics*, and one in *Strength of Materials*. The purpose of this book is to present the subject matter in an up-to-date manner with a strong design emphasis. The level is aimed at junior-senior mechanical engineering students. A primary goal was to write a text that is very easy to read and that students will enjoy reading despite the inherent dryness of the subject matter.

This textbook is designed to be an improvement over others currently available and to provide methods and techniques that take full advantage of computer-aided analysis. It emphasizes design and synthesis as well as analysis. Example problems, case studies, and solution techniques are spelled out in detail and are self-contained. All the illustrations are done in two colors. Short problems are provided in each chapter and, where appropriate, longer unstructured design-project assignments are given.

The book is independent of any particular computer program. Computer files for the solution of all the examples and case studies written in several different languages (*Mathcad*, *MATLAB*, *Excel*, and *TK Solver*) are provided on the book's website at <http://www.pearsonhighered.com/norton>. Several other programs written by the author are available from the author. These include a matrix solver (MATRIX.exe). An index of the website's content is on the website.

While this book attempts to be thorough and complete on the engineering-mechanics topics of failure theory and analysis, it also emphasizes the synthesis and design aspects of the subject to a greater degree than most other texts in print on this subject. It points out the commonality of the analytical approaches needed to design a wide variety of elements and emphasizes the use of computer-aided engineering as an approach to the design and analysis of these classes of problems. The author's approach to this course is based on over 50 years of practical experience in mechanical engineering design, both in industry and as a consultant to industry. He has taught mechanical engineering design at the university level for 40 of those years as well.

What's in the Sixth Edition?

- Twenty-one Master Lecture videos on the topics of most chapters are provided on the website. These are taken from the author's live lectures to classes at WPI. The student can watch these videos to review and enhance their understanding of the book's topics.
- Eight short videos are provided on the website in which the author demonstrates various principles of stress analysis and shows examples of common machine parts such as springs, gears, and bearings.
- Six videos that show real machinery in operation are also provided on the website.
- Over 80 problems are added with many being in SI units.
- In addition to the printed version of the text, digital e-book versions are also available. These have hotlinks to all the videos and to the downloadable content provided. There

are 37 videos. All of these are marked in the print version as well, with their URLs provided, and they can be downloaded by print-book users. A **Video Contents** is provided, and all other downloadable items are listed in the **Downloads Index**.

- The author-written programs that come with the book have been completely rewritten to improve their interface and usability, and they are now compatible with the latest operating systems and computers. Programs Linkages and DYNACAM have been completely rewritten and are much improved. Program MATRIX is updated. These computer programs undergo frequent revision to add features and enhancements. Once installed, the programs can be updated from the Start Menu. Users should occasionally check for updates.
- All the downloadable files are accessible to digital-book users through the publisher's *Mastering* website via links in the digital book. Any instructor or student who uses the print book may register on my website, <http://www.designofmachinery.com>, either as a student or instructor, and I will send them a password to access a protected site where they can download the latest versions of my computer programs, LINKAGES, DYNACAM, and MATRIX, all videos, and all files listed in the Downloads Index. Note that I personally review each of these requests for access and approve only those that are filled out completely and correctly according to the provided instructions. I require complete information and only accept university email addresses.

Philosophy

This is often the first course that mechanical engineering students see that presents them with design challenges rather than set-piece problems. Nevertheless, the type of design addressed in this course is that of *detailed design*, which is only one part of the entire design-process spectrum. In detailed design, the general concept, application, and even general shape of the required device are typically known at the outset. We are not trying to invent a new device so much as define the shape, size, and material of a particular machine element such that it will not fail under the loading and environmental conditions expected in service.

The traditional approach to the teaching of the *Elements* course has been to emphasize the design of individual machine parts, or elements, such as gears, springs, shafts, etc. One criticism that is sometimes directed at the *Elements* course (or textbook) is that it can easily become a “cookbook” collection of disparate topics that does not prepare the student to solve other types of problems not found in the recipes presented. There is a risk of this happening. It is relatively easy for the instructor (or author) to allow the course (or text) to degenerate into the mode “Well, it’s Tuesday, let’s design springs—on Friday, we’ll do gears.” If this happens, it may do the student a disservice because it doesn’t necessarily develop a fundamental understanding of the practical application of the underlying theories to design problems.

However, many of the machine elements typically addressed in this course provide superb examples of the underlying theory. If viewed in that light, and if presented in a general context, they can be an excellent vehicle for the development of student understanding of complex and important engineering theories. For example, the topic of preloaded bolts is a perfect vehicle to introduce the concept of prestressing used as a foil against fatigue loading. The student may never be called upon in practice to design a preloaded bolt, but he or she may well utilize the understanding of prestressing gained from the experience. The design of helical gears to withstand time-varying loads provides an excellent vehicle to develop the student’s understanding of combined stresses, Hertzian stresses, and fatigue failure. Thus the *elements* approach is a valid and defensible one as long as the approach taken in the text is sufficiently global. That is, it should not be allowed to degenerate into a collection of apparently unrelated exercises, but rather provide an integrated approach.

Another area in which the author has found existing texts (and *Machine Elements* courses) to be deficient is the lack of connection made between the dynamics of a system and the stress analysis of that system. Typically, these texts present their machine elements with (magically) predefined forces on them. The student is then shown how to determine the stresses and deflections caused by those forces. In real machine design, the forces are not always predefined and can, in large part, be due to the accelerations of the masses of the moving parts. However, the masses cannot be accurately determined until the geometry is defined and a stress analysis done to determine the strength of the assumed part. Thus, an impasse exists that is broken only by iteration, i.e., assume a part geometry and define its geometric and mass properties, calculate the dynamic loads due in part to the material and geometry of the part. Then calculate the stresses and deflections resulting from those forces, find out it fails, redesign, and repeat.

An Integrated Approach

The text is divided into two parts. The first part presents the fundamentals of stress, strain, deflection, materials properties, failure theories, fatigue phenomena, fracture mechanics, FEA, etc. These theoretical aspects are presented in similar fashion to other texts. The second part presents treatments of specific, common design elements used as examples of applications of the theory but also attempts to avoid presenting a string of disparate topics in favor of an integrated approach that ties the various topics together via *case studies*.

Most *Elements* texts contain many more topics and more content than can possibly be covered in a one-semester course. Before writing the first edition of this book, a questionnaire was sent to 200 U.S. university instructors of the *Elements* course to solicit their opinions on the relative importance and desirability of the typical set of topics in an *Elements* text. With each revision to second through fifth editions, users were again surveyed to determine what should be changed or added. The responses were analyzed and used to influence the structure and content of this book in all editions. One of the strongest desires originally expressed by the respondents was for *case studies* that present realistic design problems.

We have attempted to accomplish this goal by structuring the text around a series of ten case studies. These case studies present different aspects of the same design problem in successive chapters, for example, defining the static or dynamic loads on the device in Chapter 3, calculating the stresses due to the static loads in Chapter 4, and applying the appropriate failure theory to determine its safety factor in Chapter 5. Later chapters present more complex case studies, with more design content. The case study in Chapter 6 on fatigue design is one such example a real problem taken from the author's consulting practice. Chapter 8 presents FEA analyses of several of these case studies and compares those results to the classical solutions done in prior chapters.

The case studies provide a series of machine design projects throughout the book that contain various combinations of the elements normally dealt with in this type of text. The assemblies contain some collection of elements such as links subjected to combined axial and bending loads, column members, shafts in combined bending and torsion, gearsets under alternating loads, return springs, fasteners under fatigue loading, rolling element bearings, etc. This integrated approach has several advantages. It presents the student with a generic design problem in context rather than as a set of disparate, unrelated entities. The student can then see the interrelationships and the rationales for the design decisions that affect the individual elements. These more comprehensive case studies are in Part II of the text. The case studies in Part I are more limited in scope and directed to the engineering mechanics topics of the chapter. In addition to the case studies, each chapter has a selection of worked-out examples to reinforce particular topics.

Chapter 9, Design Case Studies, is devoted to the setup of three design case studies that are used in the following chapters to reinforce the concepts behind the design and analysis of shafts, springs, gears, fasteners, etc. Not all aspects of these design case studies are addressed as worked-out examples since another purpose is to provide material for student-project assignments. The author has used these case study topics as multi-week or term-long project assignments for groups or individual students with good success. Assigning open-ended project assignments serves to reinforce the design and analysis aspects of the course much better than set-piece homework assignments.

Problem Sets

Most of the 967 problem sets (767, or 79%) are independent within a chapter, responding to requests by users of the first edition to decouple them. The other 21% of the problem sets are built upon in succeeding chapters. These linked problems have the same dash number in each chapter and their problem number is **boldface** to indicate their commonality among chapters. For example, Problem 3-4 asks for a static force analysis of a trailer hitch; Problem 4-4 requests a stress analysis of the same hitch based on the forces calculated in Problem 3-4; Problem 5-4 asks for the static safety factor for the hitch using the stresses calculated in Problem 4-4; Problem 6-4 requests a fatigue-failure analysis of the same hitch, and Problem 7-4 requires a surface stress analysis. The same trailer hitch is used as an FEA case study in Chapter 8. Thus, the complexity of the underlying design problem is unfolded as new topics are introduced. An instructor who wishes to use this approach can assign problems with the same dash number in succeeding chapters. If one does not want to assign an earlier problem on which a later one is based, the solution manual data from the earlier problem can be provided to the students. Instructors who do not like interlinked problems can avoid them entirely and select from the 767 problems with nonbold problem numbers that are independent within their chapters.

Text Arrangement

Chapter 1 provides an introduction to the design process, problem formulation, safety factors, and units. Material properties are reviewed in Chapter 2 since even the student who has had a first course in material science or metallurgy typically has but a superficial understanding of the wide spectrum of engineering material properties needed for machine design. Chapter 3 presents a discussion of the fundamentals of kinematic linkages and cams. It also provides a review of static and dynamic loading analysis, including beam, vibration, and impact loading, and sets up a series of case studies that are used in later chapters to illustrate the stress and deflection analysis topics with some continuity.

The *Design of Machine Elements* course, at its core, is really an intermediate-level, applied stress-analysis course. Accordingly, a review of the fundamentals of stress and deflection analysis is presented in Chapter 4. Static failure theories are presented in detail in Chapter 5 since the students have typically not yet fully digested these concepts from their first stress-analysis course. Fracture-mechanics analysis for static loads is also introduced.

The *Elements* course is typically the student's first exposure to fatigue analysis since most introductory stress-analysis courses deal only with statically loaded problems. Accordingly, fatigue-failure theory is presented at length in Chapter 6 with the emphasis on stress-life approaches to high-cycle fatigue design, which is commonly used in the design of rotating machinery. Fracture-mechanics theory is further discussed with regard to crack propagation under cyclic loading. Strain-based methods for low-cycle fatigue analysis are not presented

but their application and purpose are introduced to the reader and bibliographic references are provided for further study. Residual stresses are also addressed. Chapter 7 presents a thorough discussion of the phenomena of wear mechanisms, surface contact stresses, and surface fatigue.

Chapter 8 provides an introduction to Finite Element Analysis (FEA). Many instructors are using the machine elements course to introduce students to FEA as well as to instruct them in the techniques of machine design. The material presented in Chapter 8 is not intended as a substitute for education in FEA theory. That material is available in many other textbooks devoted to that subject and the student is urged to become familiar with FEA theory through coursework or self-study. Instead, Chapter 8 presents proper techniques for the application of FEA to practical machine design problems. Issues of element selection, mesh refinement, and the definition of proper boundary conditions are developed in some detail. These issues are not usually addressed in books on FEA theory. Many engineers in training today will, in their professional practice, use CAD solid modeling software and commercial finite element analysis code. It is important that they have some knowledge of the limitations and proper application of those tools. This chapter can be taken up earlier in the course if desired, especially if the students are expected to use FEA to solve assigned tasks. It is relatively independent of the other chapters. Many of various chapters' problem assignments have Solidworks models of their geometry provided on the website.

These eight chapters comprise Part I of the text and lay the analytical foundation needed for design of machine elements. They are arranged to be taken up in the order presented and build upon each other with the exception of Chapter 8 on FEA.

Part II of the text presents the design of machine elements in context as parts of a whole machine. The chapters in Part II are essentially independent of one another and can be taken (or skipped) in any order that the instructor desires (except that Chapter 12 on spur gears should be studied before Chapter 13 on helical, bevel, and worm gears). It is unlikely that all topics in the book can be covered in a one-term or one semester course. Uncovered chapters will still serve as a reference for engineers in their professional practice.

Chapter 9 presents a set of design case studies to be used as assignments and as example case studies in the following chapters and also provides a set of suggested design project assignments in addition to the detailed case studies as described above. Chapter 10 investigates shaft design using the fatigue-analysis techniques developed in Chapter 6. Chapter 11 discusses fluid-film and rolling-element bearing theory and application using the theory developed in Chapter 7. Chapter 12 gives a thorough introduction to the kinematics, design and stress analysis of spur gears using the latest AGMA recommended procedures. Chapter 13 extends gear design to helical, bevel, and worm gearing. Chapter 14 covers spring design including helical compression, extension and torsion springs, as well as a thorough treatment of Belleville springs. Chapter 15 deals with screws and fasteners including power screws and preloaded fasteners. Chapter 16 presents an up-to-date treatment of the design of weldments for both static and dynamic loading. Chapter 17 presents an introduction to the design and specification of disk and drum clutches and brakes. The appendices contain material-strength data, beam tables, and stress-concentration factors, as well as answers to selected problems.

Supplements

A **Solutions Manual** is available to instructors from the publisher and **PowerPoint slides** of all figures and tables in the text are available on the publisher's website (password protected) at:

<http://www.pearsonhighered.com/>

To download these resources, choose the **Instructor Support** tab to register as an instructor and follow instructions on the site to obtain the resources provided. Mathcad files for all the problem solutions are available with the solutions manual. This computerized approach to problem solutions has significant advantages to the instructor who can easily change any assigned problem's data and instantly solve it. Thus, an essentially infinite supply of problem sets is available, going far beyond those defined in the text. The instructor also can easily prepare and solve exam problems by changing data in the supplied files.

As errata are discovered they will be posted on the author's personal website at:

<http://www.designofmachinery.com/MD/errata.html>

Professors who adopt the book may register at the author's personal website to obtain additional information relevant to the subject (syllabi, master lectures, project assignments, etc.) and the text and to download web content and updated software (password protected). Go to:

<http://designofmachinery.com/books/machine-design/professors-using-our-books-md/>

Anyone who purchases the book may register at the author's personal website to request downloads and updated software for the current edition (password protected). Go to:

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Every effort has been made to eliminate errors from this text. Any that remain are the author’s responsibility. He will greatly appreciate being informed of any errors that still remain so they can be corrected in future printings. An e-mail to norton@wpi.edu will be sufficient.

*Robert L. Norton
Mattapoisett, MA.
June 1, 2019*

Contents

PREFACE _____ **VII**

VIDEO CONTENTS _____ **XXIX**

PART I FUNDAMENTALS **1**

CHAPTER 1 INTRODUCTION TO DESIGN _____ **3**

1.1	Design	3
	Machine Design	3
1.2	A Design Process	5
1.3	Problem Formulation and Calculation	7
	Definition Stage	8
	Preliminary Design Stage	8
	Detailed Design Stage	8
	Documentation Stage	9
1.4	The Engineering Model	9
	Estimation and First-Order Analysis	9
	The Engineering Sketch	10
1.5	Computer-Aided Design and Engineering	10
	Computer-Aided Design (CAD)	11
	Computer-Aided Engineering (CAE)	12
	Computational Accuracy	15
1.6	The Engineering Report	16
1.7	Factors of Safety and Design Codes	16
	Factor of Safety	16
	Choosing a Safety Factor	17
	Design and Safety Codes	19
1.8	Statistical Considerations	20
1.9	Units	20
1.10	Summary	25
1.11	References	26
1.12	Web References	26
1.13	Bibliography	27
1.14	Problems	27

CHAPTER 2 MATERIALS AND PROCESSES	29
2.0 Introduction	29
2.1 Material-Property Definitions	29
The Tensile Test	31
Ductility and Brittleness	33
The Compression Test	35
The Bending Test	35
The Torsion Test	35
Fatigue Strength and Endurance Limit	37
Impact Resistance	38
Fracture Toughness	40
Creep and Temperature Effects	40
2.2 The Statistical Nature of Material Properties	41
2.3 Homogeneity and Isotropy	42
2.4 Hardness	42
Heat Treatment	44
Surface (Case) Hardening	45
Heat Treating Nonferrous Materials	46
Mechanical Forming and Hardening	46
2.5 Coatings and Surface Treatments	48
Galvanic Action	49
Electroplating	50
Electroless Plating	50
Anodizing	51
Plasma-Sprayed Coatings	51
Chemical Coatings	51
2.6 General Properties of Metals	52
Cast Iron	52
Cast Steels	53
Wrought Steels	53
Steel Numbering Systems	54
Aluminum	56
Titanium	58
Magnesium	59
Copper Alloys	59
2.7 General Properties of Nonmetals	60
Polymers	60
Ceramics	62
Composites	62
2.8 Selecting Materials	63
2.9 Summary	64
2.10 References	68
2.11 Web References	68
2.12 Bibliography	68
2.13 Problems	69

CHAPTER 3	KINEMATICS AND LOAD DETERMINATION	73
3.0	Introduction	73
3.1	Degree of Freedom	73
3.2	Mechanisms	74
3.3	Calculating Degree of Freedom (Mobility)	75
3.4	Common 1-DOF Mechanisms	76
	Fourbar Linkage and the Grashof Condition	76
	Sixbar Linkage	78
	Cam and Follower	79
3.5	Analyzing Linkage Motion	80
	Types of Motion	80
	Complex Numbers as Vectors	81
	The Vector Loop Equation	82
3.6	Analyzing the Fourbar Linkage	82
	Solving for Position in the Fourbar Linkage	82
	Solving for Velocity in the Fourbar Linkage	84
	Angular Velocity Ratio and Mechanical Advantage	86
	Solving for Acceleration in the Fourbar Linkage	87
3.7	Analyzing the Fourbar Crank-Slider	89
	Solving for Position in the Fourbar Crank-Slider	89
	Solving for Velocity in the Fourbar Crank-Slider	90
	Solving for Acceleration in the Fourbar Crank-Slider	91
	Other Linkages	92
3.8	Cam Design and Analysis	92
	The Timing Diagram	93
	The <i>svaj</i> Diagram	94
	Polynomials for the Double-Dwell Case	94
	Polynomials for the Single-Dwell Case	97
	Pressure Angle	99
	Radius of Curvature	100
3.9	Loading Classes For Force Analysis	101
3.10	Free-body Diagrams	103
3.11	Load Analysis	103
	Three-Dimensional Analysis	104
	Two-Dimensional Analysis	105
	Static Load Analysis	106
3.12	Two-Dimensional, Static Loading Case Studies	106
3.13	Three-Dimensional, Static Loading Case Study	121
3.14	Dynamic Loading Case Study	126
3.15	Vibration Loading	130
	Natural Frequency	130
	Dynamic Forces	132
3.16	Impact Loading	134
	Energy Method	135

3.17	Beam Loading	139
	Shear and Moment	139
	Singularity Functions	141
	Superposition	151
3.18	Summary	151
3.19	References	154
3.20	Web References	155
3.21	Bibliography	155
3.22	Problems	156

CHAPTER 4 STRESS, STRAIN, AND DEFLECTION _____ **173**

4.0	Introduction	173
4.1	Stress	173
4.2	Strain	177
4.3	Principal Stresses	177
4.4	Plane Stress and Plane Strain	180
	Plane Stress	180
	Plane Strain	180
4.5	Mohr's Circles	180
4.6	Applied Versus Principal Stresses	185
4.7	Axial Tension	186
4.8	Direct Shear Stress, Bearing Stress, and Tearout	186
	Direct Shear	187
	Direct Bearing	187
	Tearout Failure	188
4.9	Beams and Bending Stresses	188
	Beams in Pure Bending	188
	Shear Due to Transverse Loading	192
4.10	Deflection in Beams	196
	Deflection by Singularity Functions	198
	Statically Indeterminate Beams	204
4.11	Castigliano's Method	207
	Deflection by Castigliano's Method	209
	Finding Redundant Reactions with Castigliano's Method	209
4.12	Torsion	210
4.13	Combined Stresses	216
4.14	Spring Rates	218
4.15	Stress Concentration	219
	Stress Concentration Under Static Loading	220
	Stress Concentration Under Dynamic Loading	222
	Determining Geometric Stress-Concentration Factors	222
	Designing to Avoid Stress Concentrations	224
4.16	Axial Compression - Columns	226
	Slenderness Ratio	226
	Short Columns	227

Long Columns	227
End Conditions	229
Intermediate Columns	230
4.17 Stresses in Cylinders	237
Thick-Walled Cylinders	237
Thin-Walled Cylinders	238
4.18 Case Studies in Static Stress and Deflection Analysis	239
4.19 Summary	255
4.20 References	261
4.21 Bibliography	261
4.22 Problems	262
CHAPTER 5 STATIC FAILURE THEORIES	279
5.0 Introduction	279
5.1 Failure of Ductile Materials Under Static Loading	281
The von Mises-Hencky or Distortion-Energy Theory	282
The Maximum Shear-Stress Theory	288
The Maximum Normal-Stress Theory	290
Comparison of Experimental Data with Failure Theories	290
5.2 Failure of Brittle Materials Under Static Loading	294
Even and Uneven Materials	294
The Coulomb-Mohr Theory	295
The Modified-Mohr Theory	296
5.3 Fracture Mechanics	301
Fracture-Mechanics Theory	302
Fracture Toughness K_{Ic}	305
5.4 Using The Static Loading Failure Theories	309
5.5 Case Studies in Static Failure Analysis	310
5.6 Summary	321
5.7 References	324
5.8 Bibliography	325
5.9 Problems	326
CHAPTER 6 FATIGUE FAILURE THEORIES	339
6.0 Introduction	339
History of Fatigue Failure	339
6.1 Mechanism of Fatigue Failure	342
Crack Initiation Stage	343
Crack Propagation Stage	343
Fracture	344
6.2 Fatigue-Failure Models	345
Fatigue Regimes	345
The Stress-Life Approach	347
The Strain-Life Approach	347
The LEFM Approach	347

6.3	Machine-Design Considerations.....	348
6.4	Fatigue Loads.....	349
	Rotating Machinery Loading	349
	Service Equipment Loading	350
6.5	Measuring Fatigue Failure Criteria.....	351
	Fully Reversed Stresses	352
	Combined Mean and Alternating Stress	358
	Fracture-Mechanics Criteria	360
	Testing Actual Assemblies	363
6.6	Estimating Fatigue Failure Criteria.....	364
	Estimating the Theoretical Fatigue Strength S_f' or Endurance Limit S_e'	364
	Correction Factors—Theoretical Fatigue Strength or Endurance Limit	366
	Corrected Fatigue Strength S_f or Corrected Endurance Limit S_e	373
	Creating Estimated S-N Diagrams	373
6.7	Notches and Stress Concentrations.....	378
	Notch Sensitivity	379
6.8	Residual Stresses	383
6.9	Designing for High-Cycle Fatigue	388
6.10	Designing for Fully Reversed Uniaxial Stresses.....	388
	Design Steps for Fully Reversed Stresses with Uniaxial Loading	389
6.11	Designing for Fluctuating Uniaxial Stresses	396
	Creating the Modified-Goodman Diagram	397
	Applying Stress-Concentration Effects with Fluctuating Stresses	400
	Determining the Safety Factor with Fluctuating Stresses	402
	Design Steps for Fluctuating Stresses	405
6.12	Designing for Multiaxial Stresses in Fatigue.....	412
	Frequency and Phase Relationships	413
	Fully Reversed Simple Multiaxial Stresses	413
	Fluctuating Simple Multiaxial Stresses	414
	Complex Multiaxial Stresses	415
6.13	A General Approach to High-Cycle Fatigue Design	417
6.14	A Case Study in Fatigue Design	422
6.15	Summary.....	435
6.16	References	439
6.17	Bibliography	442
6.18	Problems.....	443
7.0	Introduction	457
CHAPTER 7 SURFACE FAILURE		457
7.1	Surface Geometry	459
7.2	Mating Surfaces	461
7.3	Friction.....	462
	Effect of Roughness on Friction	463
	Effect of Velocity on Friction	463
	Rolling Friction	463
	Effect of Lubricant on Friction	464

7.4	Adhesive Wear	464
	The Adhesive-Wear Coefficient	467
7.5	Abrasive Wear	468
	Abrasive Materials	471
	Abrasion-Resistant Materials	471
7.6	Corrosion Wear	472
	Corrosion Fatigue	473
	Fretting Corrosion	473
7.7	Surface Fatigue	474
7.8	Spherical Contact	476
	Contact Pressure and Contact Patch in Spherical Contact	476
	Static Stress Distributions in Spherical Contact	478
7.9	Cylindrical Contact	482
	Contact Pressure and Contact Patch in Parallel Cylindrical Contact	482
	Static Stress Distributions in Parallel Cylindrical Contact	483
7.10	General Contact	486
	Contact Pressure and Contact Patch in General Contact	486
	Stress Distributions in General Contact	488
7.11	Dynamic Contact Stresses	491
	Effect of a Sliding Component on Contact Stresses	491
7.12	Surface Fatigue Failure Models—Dynamic Contact	498
7.13	Surface Fatigue Strength	501
7.14	Summary	508
7.15	References	512
7.16	Problems	514
CHAPTER 8 FINITE ELEMENT ANALYSIS		521
8.0	Introduction	521
	Stress and Strain Computation	522
8.1	Finite Element Method	523
8.2	Element Types	525
	Element Dimension and Degree of Freedom (DOF)	525
	Element Order	526
	H-Elements Versus P-Elements	527
	Element Aspect Ratio	527
8.3	Meshing	527
	Mesh Density	528
	Mesh Refinement	528
	Convergence	528
8.4	Boundary Conditions	532
8.5	Applying Loads	542
8.6	Testing the Model (Verification)	543
8.7	Modal Analysis	546
8.8	Case Studies	548
8.9	Summary	558
8.10	References	559

8.11	Bibliography	559
8.12	Web Resources	559
8.13	Problems.....	560

PART II MACHINE DESIGN _____ 561

CHAPTER 9 DESIGN CASE STUDIES _____ 563

9.0	Introduction	563
9.1	Case Study 8—A Portable Air Compressor.....	564
9.2	Case Study 9—A Hay-Bale Lifter	567
9.3	Case Study 10—A Cam-Testing Machine.....	571
9.4	Summary.....	577
9.5	References	577
9.6	Design Projects.....	578

CHAPTER 10 SHAFTS, KEYS, AND COUPLINGS _____ 589

10.0	Introduction	589
10.1	Shaft Loads	589
10.2	Attachments and Stress Concentrations.....	591
10.3	Shaft Materials.....	593
10.4	Shaft Power.....	593
10.5	Shaft Loads	594
10.6	Shaft Stresses.....	594
10.7	Shaft Failure in Combined Loading.....	595
10.8	Shaft Design	596
	General Considerations	596
	Design for Fully Reversed Bending and Steady Torsion	597
	Design for Fluctuating Bending and Fluctuating Torsion	599
10.9	Shaft Deflection	606
	Shafts as Beams	607
	Shafts as Torsion Bars	607
10.10	Keys and Keyways	610
	Parallel Keys	610
	Tapered Keys	611
	Woodruff Keys	612
	Stresses in Keys	612
	Key Materials	613
	Key Design	613
	Stress Concentrations in Keyways	614
10.11	Splines	618
10.12	Interference Fits	620
	Stresses in Interference Fits	620
	Stress Concentration in Interference Fits	621
	Fretting Corrosion	622

10.13	Flywheel Design	625
	Energy Variation in a Rotating System	626
	Determining the Flywheel Inertia	628
	Stresses in Flywheels	630
	Failure Criteria	631
10.14	Critical Speeds of Shafts	633
	Lateral Vibration of Shafts and Beams—Rayleigh’s Method	635
	Shaft Whirl	637
	Torsional Vibration	639
	Two Disks on a Common Shaft	640
	Multiple Disks on a Common Shaft	641
	Controlling Torsional Vibrations	642
10.15	Couplings	644
	Rigid Couplings	645
	Compliant Couplings	646
10.16	Case Study 8B.....	648
	Designing Driveshafts for a Portable Air Compressor	648
10.17	Summary.....	652
10.18	References	654
10.19	Problems.....	655
CHAPTER 11 BEARINGS AND LUBRICATION		665
11.0	Introduction	665
	A Caveat	667
11.1	Lubricants	667
11.2	Viscosity	669
11.3	Types of Lubrication.....	670
	Full-Film Lubrication	671
	Boundary Lubrication	673
11.4	Material Combinations in Sliding Bearings.....	673
11.5	Hydrodynamic Lubrication Theory	674
	Petroff’s Equation for No-Load Torque	675
	Reynolds’ Equation for Eccentric Journal Bearings	676
	Torque and Power Losses in Journal Bearings	681
11.6	Design of Hydrodynamic Bearings.....	682
	Design Load Factor—The Ocvirk Number	682
	Design Procedures	684
11.7	Nonconforming Contacts.....	688
11.8	Rolling-element bearings	695
	Comparison of Rolling and Sliding Bearings	696
	Types of Rolling-Element Bearings	696
11.9	Failure of Rolling-element bearings.....	700
11.10	Selection of Rolling-element bearings	701
	Basic Dynamic Load Rating C	701
	Modified Bearing Life Rating	702
	Basic Static Load Rating C_0	703

Combined Radial and Thrust Loads	704
Calculation Procedures	705
11.11 Bearing Mounting Details	707
11.12 Special Bearings	708
11.13 Case Study 10B	710
11.14 Summary	712
Important Equations Used in This Chapter	713
11.15 References	715
11.16 Problems	717
CHAPTER 12 SPUR GEARS	725
12.0 Introduction	725
12.1 Gear Tooth Theory	727
The Fundamental Law of Gearing	727
The Involute Tooth Form	728
Pressure Angle	729
Gear Mesh Geometry	730
Rack and Pinion	731
Changing Center Distance	731
Backlash	733
Relative Tooth Motion	733
12.2 Gear Tooth Nomenclature	733
12.3 Interference and Undercutting	736
Unequal-Addendum Tooth Forms	737
12.4 Contact Ratio	738
12.5 Gear Trains	740
Simple Gear Trains	740
Compound Gear Trains	741
Reverted Compound Trains	742
Epicyclic or Planetary Gear Trains	743
12.6 Gear Manufacturing	746
Forming Gear Teeth	746
Machining	747
Roughing Processes	747
Finishing Processes	747
Gear Quality	749
12.7 Loading on Spur Gears	749
12.8 Stresses in Spur Gears	752
Bending Stresses	752
Surface Stresses	761
12.9 Gear Materials	765
Material Strengths	766
Bending-Fatigue Strengths for Gear Materials	767
Surface-Fatigue Strengths for Gear Materials	769
12.10 Lubrication of Gearing	775
12.11 Design of Spur Gears	776

12.12	Case Study 8C	777
12.13	Summary	783
12.14	References	784
12.15	Problems	785
CHAPTER 13 HELICAL, BEVEL, AND WORM GEARS		791
13.0	Introduction	791
13.1	Helical Gears	791
	Helical Gear Geometry	793
	Helical-Gear Forces	794
	Virtual Number of Teeth	795
	Contact Ratios	796
	Stresses in Helical Gears	796
13.2	Bevel Gears	804
	Bevel-Gear Geometry and Nomenclature	804
	Bevel-Gear Mounting	806
	Forces on Bevel Gears	806
	Stresses in Bevel Gears	806
13.3	Wormsets	810
	Materials for Wormsets	813
	Lubrication in Wormsets	814
	Forces in Wormsets	814
	Wormset Geometry	814
	Rating Methods	815
	A Design Procedure for Wormsets	817
13.4	Case Study 9B	817
13.5	Summary	821
13.6	References	825
13.7	Problems	825
CHAPTER 14 SPRING DESIGN		829
14.0	Introduction	829
14.1	Spring Rate	829
14.2	Spring Configurations	832
14.3	Spring Materials	834
	Spring Wire	834
	Flat Spring Stock	837
14.4	Helical Compression Springs	838
	Spring Lengths	838
	End Details	839
	Active Coils	839
	Spring Index	840
	Spring Deflection	840
	Spring Rate	840
	Stresses in Helical Compression Spring Coils	840
	Helical Coil Springs of Nonround Wire	842
	Residual Stresses	843

	Buckling of Compression Springs	844
	Compression-Spring Surge	844
	Allowable Strengths for Compression Springs	846
	The Torsional-Shear S-N Diagram for Spring Wire	847
	The Modified-Goodman Diagram for Spring Wire	849
14.5	Designing Helical Compression Springs for Static Loading	851
14.6	Designing Helical Compression Springs for Fatigue Loading	856
14.7	Helical Extension Springs	863
	Active Coils in Extension Springs	863
	Spring Rate of Extension Springs	864
	Spring Index of Extension Springs	864
	Coil Preload in Extension Springs	864
	Deflection of Extension Springs	864
	Coil Stresses in Extension Springs	865
	End Stresses in Extension Springs	865
	Surging in Extension Springs	866
	Material Strengths for Extension Springs	866
	Design of Helical Extension Springs	866
14.8	Helical Torsion Springs	874
	Terminology for Torsion Springs	875
	Number of Coils in Torsion Springs	875
	Deflection of Torsion Springs	875
	Spring Rate of Torsion Springs	876
	Coil Closure	876
	Coil Stresses in Torsion Springs	876
	Material Parameters for Torsion Springs	877
	Safety Factors for Torsion Springs	878
	Designing Helical Torsion Springs	878
14.9	Belleville Spring Washers	881
	Load-Deflection Function for Belleville Washers	882
	Stresses in Belleville Washers	884
	Static Loading of Belleville Washers	885
	Dynamic Loading	885
	Stacking Springs	885
	Designing Belleville Springs	886
14.10	Case Study 10C	888
14.11	Summary	893
14.12	References	896
14.13	Problems	897
CHAPTER 15 SCREWS AND FASTENERS		903
15.0	Introduction	903
15.1	Standard Thread Forms	906
	Tensile Stress Area	907
	Standard Thread Dimensions	908
15.2	Power Screws	909
	Square, Acme, and Buttress Threads	910
	Power Screw Application	910
	Power Screw Force and Torque Analysis	912

Friction Coefficients	913
Self-Locking and Back-Driving of Power Screws	914
Screw Efficiency	915
Ball Screws	915
15.3 Stresses in Threads	918
Axial Stress	919
Shear Stress	919
Torsional Stress	920
15.4 Types of Screw Fasteners	920
Classification by Intended Use	921
Classification by Thread Type	921
Classification by Head Style	921
Nuts and Washers	923
15.5 Manufacturing Fasteners	923
15.6 Strengths of Standard Bolts and Machine Screws	925
15.7 Preloaded Fasteners in Tension	925
Preloaded Bolts Under Static Loading	929
Preloaded Bolts Under Dynamic Loading	933
15.8 Determining the Joint Stiffness Factor	939
Joints With Two Plates of the Same Material	941
Joints With Two Plates of Different Materials	941
Gasketed Joints	943
15.9 Controlling Preload	948
The Turn-of-the-Nut Method	949
Torque-Limited Fasteners	949
Load-Indicating Washers	949
Torsional Stress Due to Torquing of Bolts	950
15.10 Fasteners in Shear	950
Dowel Pins	952
Centroids of Fastener Groups	953
Determining Shear Loads on Fasteners	954
15.11 Case Study 8D	956
15.12 Summary	961
15.13 References	964
15.14 Bibliography	964
15.15 Problems	965
CHAPTER 16 WELDMENTS	973
16.0 Introduction	973
16.1 Welding Processes	975
Types of Welding in Common Use	976
Why Should a Designer Be Concerned with the Welding Process?	977
16.2 Weld Joints and Weld Types	977
Joint Preparation	979
Weld Specification	979
16.3 Principles of Weldment Design	979

16.4	Static Loading of Welds	981
16.5	Static Strength of Welds.....	982
	Residual Stresses in Welds	983
	Direction of Loading	983
	Allowable Shear Stress for Statically Loaded Fillet and PJP Welds	983
16.6	Dynamic Loading of Welds.....	986
	Effect of Mean Stress on Weldment Fatigue Strength	986
	Are Correction Factors Needed For Weldment Fatigue Strength?	986
	Effect of Weldment Configuration on Fatigue Strength	987
	Is There an Endurance Limit for Weldments?	991
	Fatigue Failure in Compression Loading?	992
16.7	Treating a Weld as a Line.....	993
16.8	Eccentrically Loaded Weld Patterns.....	999
16.9	Design Considerations for Weldments in Machines	1000
16.10	Summary.....	1001
16.11	References	1002
16.12	Problems.....	1003
CHAPTER 17 CLUTCHES AND BRAKES		1007
17.0	Introduction	1007
17.1	Types of Brakes and Clutches	1009
17.2	Clutch/Brake Selection and Specification.....	1014
17.3	Clutch and Brake Materials.....	1016
17.4	Disk Clutches.....	1016
	Uniform Pressure	1017
	Uniform Wear	1017
17.5	Disk Brakes	1019
17.6	Drum Brakes	1020
	Short-Shoe External Drum Brakes	1021
	Long-Shoe External Drum Brakes	1023
	Long-Shoe Internal Drum Brakes	1027
17.7	Summary.....	1027
17.8	References	1030
17.9	Bibliography	1030
17.10	Problems.....	1031
APPENDICES		1035
A	Material Properties.....	1035
B	Beam Tables.....	1043
C	Stress-Concentration Factors	1047
D	Answers to Selected Problems.....	1055
INDEX		1065
DOWNLOADS INDEX		1078

VIDEO CONTENTS

The Sixth Edition has a collection of **Master Lecture Videos** and **Tutorials** made by the author over a 31-year period while teaching at Worcester Polytechnic Institute. The lectures were recorded in a classroom in front of students in 2011/2012. Tutorials were done in a recording studio and were intended as supplements to class lectures. There are 37 instructional videos in total. One is a short introduction to the master lecture series and 20 are “50-minute” lectures. Eight are short tutorials and eight are demonstrations of machinery. The run times of all videos are noted in the tables.

The sixth edition is available both as a print book and as digital media. The digital, e-book versions have active links that allow these videos to be run while reading the book. The print edition notes the names and URLs of all the videos in the text at their links.

In addition to the lecture videos, all the digital content that was with the fifth and earlier editions is still available as downloads, including the author-written programs **LINKAGES**, **DYNACAM**, and **MATRIX**. An index of all the non-video downloadable files is in the **Downloads Index**. In the digital e-book versions, these are hotlinked to the text. The URL of each video is also provided for print-book readers to download them.

Any instructor or student who uses the book may register on my website, <http://www.designofmachinery.com>, either as a student or instructor, and I will send them a password to access a protected site where they can download the latest versions of my computer programs, **LINKAGES**, **DYNACAM**, and **MATRIX**. They can also download the 33 videos and all the files listed in the **Downloads Index**. Note that I personally review each of these requests for access and will approve only those that are filled out completely and correctly according to the provided instructions. I require complete information and only accept university email addresses.

LECTURE VIDEOS

(Concatenate this URL with any filename below to run a video)

Chapter	Lecture	Topic	http://www.designofmachinery.com/MD/	Run Time
	1	Introduction	01_Introduction.mp4	03:30
4	2	Stress Review	02_Stress_Review.mp4	53:40
4	3	Stress Distribution	03_Stress_Distribution.mp4	50:52
4	4	Combined Stress, Stress Concentration, Columns	04_Combined_stress_stress_concentration_columns.mp4	54:11
5	5	Ductile Failure Theory	05_Ductile_Failure_Theory.mp4	46:02
5	6	Brittle Failure Theory	06_Brittle_Failure_Theory.mp4	51:02
6	7	Fatigue Failure Theory	07_Fatigue_Failure_Theory.mp4	55:49
6	8	Fully Reversed Loads	08_Fully_Reversed_Loads.mp4	52:59
6	9	Fluctuating Loads	09_Fluctuating_Loads.mp4	54:14
10	10	Shaft Design I	10_Shaft_Design_I.mp4	44:44
10	11	Shaft Design II	11_Shaft_Design_II.mp4	47:20
7	12	Wear and Surface Fatigue	12_Wear_and_Surface_Fatigue.mp4	52:25
12	13	Spur Gear Design I	13_Spur_Gear_Design_I.mp4	51:31
12	14	Spur Gear Design II	14_Spur_Gear_Design_II.mp4	50:37
14	15	Spring Design I	15_Spring_Design_I.mp4	52:20
14	16	Spring Design II	16_Spring_Design_II.mp4	47:46
11	17	Bearings and Lubrication	17_Bearings_and_Lubrication.mp4	50:07
11	18	Rolling Element Bearings	18_Rolling_Element_Bearings.mp4	46:54
15	19	Power Screws and Fasteners	19_Power_Screws_and_Fasteners.mp4	44:42
15	20	Preloaded Fasteners	20_Preloaded_Fasteners.mp4	48:22
8	21	Finite Element Analysis	21_Finite_Element_Analysis.mp4	52:28

TUTORIAL VIDEOS*(Concatenate this URL with any filename below to run a video)*

Topic	http://www.designofmachinery.com/MD/	Run Time
Bearings	Bearings.mp4	09:11
Bending Stress	Bending_Stress.mp4	05:57
Columns	Columns.mp4	01:52
Failure Modes	Failure_Modes.mp4	09:41
Gears	Gears.mp4	22:07
Springs	Springs.mp4	20:06
Stress Cube	Stress_Cube.mp4	05:04
Torsion	Torsion.mp4	03:13

DEMONSTRATION VIDEOS*(Concatenate this URL with any filename below to run a video)*

Topic	http://www.designofmachinery.com/MD/	Run Time
Boot Testing Machine	Boot_Tester.mp4	19:02
Bottle Printing Machine	Bottle_Printing_Machine.mp4	09:49
Cam Machine	Cam_Machine.mp4	21:28
Fourbar Machine	Fourbar_Machine.mp4	35:38
Pick and Place Mechanism	Pick_and_Place_Mechanism.mp4	36:35
Spring Manufacturing Machinery	Spring_Manufacturing.mp4	12:23
Spring Surge and Spring Failure	Fatigue_Failure.mp4	03:46
Vibration Testing	Vibration_Testing.mp4	05:51

Note that you can download a PDF file containing hyperlinks to all the video content listed in the above tables. This allows print-book readers to easily access the videos without having to type in each URL as noted in the tables. Download the file:

http://www.designofmachinery.com/MD/Video_Links_for_Machine_Design_6ed.pdf

Part
I

FUNDAMENTALS



INTRODUCTION TO DESIGN

*Learning without thought is labor lost;
thought without learning is perilous.*

CONFUCIUS, 6TH CENTURY B.C.

1.1 DESIGN *View the introductory video (03:30)*[†]

What is design? Wallpaper is designed. You may be wearing “designer” clothes. Automobiles are “designed” in terms of their external appearance. The term *design* clearly encompasses a wide range of meaning. In the above examples, design refers primarily to the object’s aesthetic appearance. In the case of the automobile, all of its other aspects also involve design. Its mechanical internals (engine, brakes, suspension, etc.) must be designed, more likely by engineers than by artists, though even the engineer gets to exhibit some artistry when designing machinery.

The word design is from the Latin word *designare* meaning *to designate, or mark out*. Design means many things. It can refer to the design of an artistic work or the appearance of a product. We are more concerned here with engineering design than with artistic design. **Engineering design** can be defined as *The process of applying the various techniques and scientific principles for the purpose of defining a device, a process, or a system in sufficient detail to permit its realization.*

Machine Design

This text is concerned with one aspect of engineering design—**machine design**. Machine design deals with the creation of machinery that works safely, reliably, and well. A **machine** can be defined as: *A system of elements arranged to transmit motion and energy in a predetermined and controlled fashion, or even more simply as: A system to control force and motion.*

[†] http://www.designofmachinery.com/MD/01_Introduction.mp4

Title-page photograph courtesy of Boeing Commercial Airplane Co. Inc., Seattle, Wash.

The notion of **useful work** is basic to a machine's function, as there is almost always some energy transfer involved. The mention of **forces** and **motion** is also critical to our concerns, as, in converting energy from one form to another, machines **create motion** and **develop forces**. It is the engineer's task to define and calculate those motions, forces, and changes in energy in order to determine the sizes, shapes, and materials needed for each of the interrelated parts in the machine. This is the essence of **machine design**.

While one must, of necessity, design a machine one part at a time, it is crucial to recognize that each part's function and performance (and thus its design) are dependent on many other interrelated parts within the same machine. Thus, we are going to attempt to "design the whole machine" here, rather than simply designing individual elements in isolation from one another. To do this we must draw upon a common body of engineering knowledge encountered in previous courses, e.g., statics, dynamics, mechanics of materials (stress analysis), and material properties. Brief reviews and examples of these topics are included in the early chapters of this book.

The ultimate goal in machine design is to size and shape the parts (machine elements) and choose appropriate materials and manufacturing processes so that the resulting machine can be expected to perform its intended function without failure. This requires that the engineer be able to calculate and predict the mode and conditions of failure for each element and then design it to prevent that failure. This in turn requires that a **stress and deflection analysis** be done for each part. Since stresses are a function of the applied and inertial loads, and of the part's geometry, an analysis of the forces, moments, torques, and the dynamics of the system must be done before the stresses and deflections can be completely calculated.

If the "machine" in question has no moving parts, then the design task becomes much simpler, because only a static force analysis is required. But if the machine has no moving parts, it is not much of a machine (and doesn't meet the definition above); it is then a **structure**. Structures also need to be designed against failure, and, in fact, large external structures (bridges, buildings, etc.) are also subjected to dynamic loads from wind, earthquakes, traffic, etc., and thus must also be designed for these conditions. Structural dynamics is an interesting subject but one which we will not address in this text. We will concern ourselves with the problems associated with machines that move. If the machine's motions are very slow and the accelerations negligible, then a static force analysis will suffice. But if the machine has significant accelerations within it, then a dynamic force analysis is needed and the accelerating parts become "victims of their own mass."

In a static structure, such as a building's floor, designed to support a particular weight, the safety factor of the structure can be increased by adding appropriately distributed material to its structural parts. Though it will be heavier (more "dead" weight), if properly designed it may nevertheless carry more "live" weight (payload) than it did before, still without failure. In a dynamic machine, adding weight (mass) to moving parts may have the opposite effect, reducing the machine's safety factor, its allowable speed, or its payload capacity. This is because some of the loading that creates stresses in the moving parts is due to the inertial forces predicted by **Newton's second law**, $F = ma$. Since the accelerations of the moving parts in the machine are dictated by its kinematic design and by its running speed, adding mass to moving parts will increase the inertial loads on those same parts unless their kinematic accelerations are reduced by slowing its operation. Even though the added mass may increase the strength of the part, that benefit may be reduced or cancelled by the resultant increases in inertial forces.

Iteration

Thus, we face a dilemma at the initial stages of machine design. Generally, before reaching the stage of sizing the parts, the kinematic motions of the machine will have already been defined. External forces provided by the “outside world” on the machine are also often known. Note that in some cases, the external loads on the machine will be very difficult to predict—for example, the loads on a moving automobile. The designer cannot predict with accuracy what environmental loads the user will subject the machine to (potholes, hard cornering, etc.). In such cases, statistical analysis of empirical data gathered from actual testing can provide some information for design purposes.

What remain to be defined are the inertial forces that will be generated by the known kinematic accelerations acting on the as yet undefined masses of the moving parts. The dilemma can be resolved only by **iteration**, which means *to repeat, or to return to a previous state*. We must assume some trial configuration for each part, use the mass properties (mass, *CG* location, and mass moment of inertia) of that trial configuration in a dynamic force analysis to determine the forces, moments, and torques acting on the part, and then use the cross-sectional geometry of the trial design to calculate the resulting stresses. In general, accurately determining all the loads on a machine is the most difficult task in the design process. If the loads are known, the stresses can be calculated.

Most likely, on the first trial, we will find that our design fails because the materials cannot stand the levels of stress presented. We must then redesign the parts (iterate) by changing shapes, sizes, materials, manufacturing processes, or other factors in order to reach an acceptable design. It is generally not possible to achieve a successful result without making several iterations through this design process. Note also that a change to the mass of one part will also affect the forces applied to parts connected to it and thus require their redesign also. It is truly the design of **interrelated parts**.

1.2 A DESIGN PROCESS*

The process of design is essentially an exercise in applied creativity. Various “design processes” have been defined to help organize the attack upon the “unstructured problem,” i.e., one for which the problem definition is vague and for which many possible solutions exist. Some of these design process definitions contain only a few steps and others a detailed list of 25 steps. One version of a design process is shown in Table 1-1, which lists ten steps.^[2] The initial step, **Identification of Need**, usually consists of an ill-defined and vague problem statement. The development of **Background Research** information (step 2) is necessary to fully define and understand the problem, after which it is possible to restate the **Goal** (step 3) in a more reasonable and realistic way than in the original problem statement.

Step 4 calls for the creation of a detailed set of **Task Specifications** which bound the problem and limit its scope. The **Synthesis** step (5) is one in which as many alternative design approaches as possible are sought, usually without regard (at this stage) for their value or quality. This is also sometimes called the **Ideation and Invention** step, in which the largest possible number of creative solutions are generated.

In step 6, the possible solutions from the previous step are **Analyzed** and either accepted, rejected, or modified. The most promising solution is **Selected** at step 7. Once an acceptable design is selected, the **Detailed Design** (step 8) can be done, in which all the loose ends are tied up, complete engineering drawings made, vendors identified,

* Adapted from Norton, *Design of Machinery*, 5ed. McGraw-Hill, New York, 2012, with the publisher’s permission.

Table 1-1 A Design Process

1	Identification of need
2	Background research
3	Goal statement
4	Task specifications
5	Synthesis
6	Analysis
7	Selection
8	Detailed design
9	Prototyping and testing
10	Production

manufacturing specifications defined, etc. The actual construction of the working design is first done as a **Prototype** in step 9 and finally in quantity in **Production** at step 10. A more complete discussion of this design process can be found in reference 2, and a number of references on the topics of creativity and design are provided in the bibliography at the end of this chapter.

The above description may give an erroneous impression that this process can be accomplished in a linear fashion as listed. On the contrary, **iteration is required within the entire process**, moving from any step back to any previous step, in all possible combinations, and doing this repeatedly. The best ideas generated at step 5 will invariably be discovered to be flawed when later analyzed. Thus, a return to at least the Ideation step will be necessary in order to generate more solutions. Perhaps a return to the Background Research phase may be necessary to gather more information. The Task Specifications may need to be revised if it turns out that they were unrealistic. In other words, anything is “fair game” in the design process, including a redefinition of the problem, if necessary. One cannot design in a linear fashion. It’s three steps forward and two (or more) back, until you finally emerge with a working solution.

Theoretically, we could continue this iteration on a given design problem forever, continually creating small improvements. Inevitably, the incremental gains in function or reductions in cost will tend toward zero with time. At some point, we must declare the design “good enough” and ship it. Often someone else (most likely, the boss) will snatch it from our grasp and ship it over our protests that it isn’t yet “perfect.” Machines that have been around a long time and that have been improved by many designers reach a level of “perfection” that makes them difficult to improve upon. One example is the ordinary bicycle. Though inventors continue to attempt to improve this machine, the basic design has become fairly static after more than a century of development.

In machine design, the early design-process steps usually involve the **Type Synthesis** of suitable kinematic configurations, which can provide the necessary motions. Type synthesis involves the choice of the *type of mechanism best suited to the problem*. This is a difficult task for the student, as it requires some experience and knowledge of the various types of mechanisms that exist and that might be feasible from a performance and manufacturing standpoint. As an example, assume that the task is to design a device

to track the constant-speed, straight-line motion of a part on a conveyor belt and attach a second part to it as it passes by. This has to be done with good accuracy and repeatability and must be reliable and inexpensive. You might not be aware that this task could be accomplished by any of the following devices:

- a straight-line linkage
- a cam and follower
- an air cylinder
- a hydraulic cylinder
- a robot
- a solenoid

Each of these solutions, while possible, may not be optimal or even practical. Each has good and bad points. The straight-line linkage is large and may have undesirable accelerations; the cam and follower is expensive but is accurate and repeatable. The air cylinder is inexpensive but noisy and unreliable. The hydraulic cylinder and the robot are more expensive. The inexpensive solenoid has high impact loads and velocities. So, the choice of device type can have a big effect on design quality. A bad choice at the type-synthesis stage can create major problems later on. The design might have to be changed after completion at great expense. Design is essentially an exercise in trade-offs. There is usually no clear-cut solution to a real engineering design problem.

Once the type of required mechanism is defined, its detailed kinematics must be synthesized and analyzed. The motions of all moving parts and their time derivatives through acceleration must be calculated in order to be able to determine the dynamic forces on the system. (See reference 2 for more information on this aspect of machine design.)

In the context of machine design addressed in this text, we will not exercise the entire design process as described in Table 1-1. Rather, we will propose examples, problems, and case studies that already have had steps 1–4 defined. The type synthesis and kinematic analysis will already be done, or at least set up, and the problems will be structured to that degree. The tasks remaining will largely involve steps 5 through 8, with a concentration on **synthesis** (step 5) and **analysis** (step 6).

Synthesis and analysis are the “two faces” of machine design, like two sides of the same coin. **Synthesis** means *to put together* and **analysis** means *to decompose, to take apart, to resolve into its constituent parts*. Thus, they are opposites, but they are symbiotic. We cannot take apart “nothing,” thus we must first synthesize something in order to analyze it. When we analyze it, we will probably find it lacking, requiring further synthesis, and then further analysis *ad nauseam*, finally iterating to a better solution. You will need to draw heavily upon your understanding of statics, dynamics, and mechanics of materials to accomplish this.

1.3 PROBLEM FORMULATION AND CALCULATION

It is extremely important for every engineer to develop good and careful computational habits. Solving complicated problems requires an organized approach. Design problems also require good record-keeping and documentation habits in order to record the many assumptions and design decisions made along the way so that the designer’s thought process can be later reconstructed if redesign is necessary.

* If there is a possibility of a patentable invention resulting from the design, then the notebook should be permanently bound (not loose-leaf), and its pages should be consecutively numbered, dated, and witnessed by someone who understands the technical content.

A suggested procedure for the designer is shown in Table 1-2, which lists a set of subtasks appropriate to most machine-design problems of this type. These steps should be documented for each problem in a neat fashion, preferably in a bound notebook in order to maintain their chronological order.*

Definition Stage

In your design notebook, first **Define the Problem** clearly in a concise statement. The “**givens**” for the particular task should be clearly listed, followed by a record of the **assumptions** made by the designer about the problem. Assumptions expand upon the given (known) information to further constrain the problem. For example, one might assume the effects of friction to be negligible in a particular case, or assume that the weight of the part can be ignored because it will be small compared to the applied or dynamic loads expected.

Preliminary Design Stage

Once the general constraints are defined, some **Preliminary Design Decisions** must be made in order to proceed. The reasons and justifications for these decisions should be documented. For example, we might decide to try a solid, rectangular cross section for a connecting link and choose aluminum as a trial material. On the other hand, if we recognized from our understanding of the problem that this link would be subjected to significant accelerations of a time-varying nature that would repeat for millions of cycles, a better design decision might be to use a hollow or I-beam section in order to reduce its mass and also to choose steel for its infinite fatigue life. Thus, these design decisions can have significant effect on the results and will often have to be changed or abandoned as we iterate through the design process. It has often been noted that 90% of a design’s characteristics may be determined in the first 10% of the total project time, during which these preliminary design decisions are made. If they are bad decisions, it may not be possible to save the bad design through later modifications without essentially starting over. The preliminary design concept should be documented at this stage with clearly drawn and labeled **Design Sketches** that will be understandable to another engineer or even to oneself after some time has passed.

Detailed Design Stage

With a tentative design direction established we can create one or more **engineering** (mathematical) **models** of the element or system in order to analyze it. These models will usually include a loading model consisting of free-body diagrams which show all forces, moments, and torques on the element or system and the appropriate equations for their calculation. Models of the stress and deflection states expected at locations of anticipated failure are then defined with appropriate stress and deflection equations.

Analysis of the design is then done using these models and the safety or failure of the design determined. The results are **evaluated** in conjunction with the properties of the chosen **engineering materials** and a decision made whether to proceed with this design or iterate to a better solution by returning to an earlier step of the process.

Table 1-2 Problem Formulation and Calculation

1	Define the problem	}	Definition stage
2	State the givens		
3	Make appropriate assumptions		
4	Preliminary design decisions	}	Preliminary design stage
5	Design sketches		
6	Mathematical models	}	Detailed design stage
7	Analysis of the design		
8	Evaluation		
9	Document results	}	Documentation stage

Documentation Stage

Once sufficient iteration through this process provides satisfactory results, the **documentation** of the element's or system's design should be completed in the form of detailed engineering drawings, material and manufacturing specifications, etc. If properly approached, a great deal of the documentation task can be accomplished concurrent with the earlier stages simply by keeping accurate and neat records of all assumptions, computations, and design decisions made throughout the process.

1.4 THE ENGINEERING MODEL

The success of any design is highly dependent on the validity and appropriateness of the engineering models used to predict and analyze its behavior in advance of building any hardware. Creating a useful engineering model of a design is probably the most difficult and challenging part of the whole process. Its success depends a great deal on experience as well as skill. Most important is a thorough understanding of the first principles and fundamentals of engineering. The engineering model that we are describing here is an amorphous thing that may consist of some sketches of the geometric configuration and some equations that describe its behavior. It is a mathematical model that describes the physical behavior of the system. This engineering model invariably requires the use of computers to exercise it. Using computer tools for analyzing engineering models is discussed in the next section. A physical model or prototype usually comes later in the process and is needed to prove the validity of the engineering model through experiments.

Estimation and First-Order Analysis

The value of making even very simplistic engineering models of your preliminary designs cannot be overemphasized. Often, at the outset of a design, the problem is so loosely and poorly defined that it is difficult to develop a comprehensive and thorough model in the form of equations that fully describe the system. The engineering student is used to problems that are fully structured, of a form such as "*Given A, B, and C, find D.*" If one can identify the appropriate equations (model) to apply to such a problem, it is relatively easy to determine an answer (which might even match the one in the back of the book).