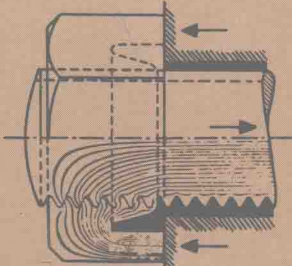
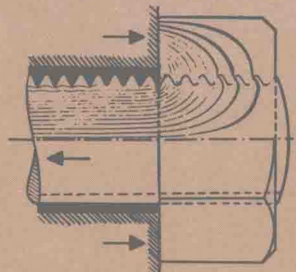
DESIGN OF MACHINE AND STRUCTURAL PARTS





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To Nicki and Kelly

PREFACE

This book was written for students of product, machine, and structural design. Since design involves geometry, the ability to sketch and draw the shapes and forms of parts is requisite. This book concentrates on presenting the principles of form design and how specific forms and loading systems affect part stresses and rigidities.

This book is intended to supplement the study of component design analysis. It is assumed that the user has had basic courses in statics and strength of materials. The objective is to provide numerous examples and illustrations for improving the strength and minimizing the weight of parts. Once learned, the principles presented here can be used for the efficient form synthesis of machine and structural parts. The book can also serve as a review of strength of materials and will allow the student to become a specialist in the initial synthesis phase of design.

The chapters depend upon, and largely follow one another, building on previously developed principles and ideas. The first three chapters of the book serve to review as well as extend the basic background. The next few chapters deal with the application of some fundamental principles to specific parts and structures. The final chapter deals with the effect of shape and loading system on rigidity. For a person with a background in strength of materials, the chapters could be studied in almost any order. The principles presented are fundamental to the form design of machine and structural parts and are described in detail.

Although much of the first three chapters is a review of statics and strength of materials, several sections are of particular importance. In Chapter 1, Section 1-3 deals with free body diagrams. Most engineers recognize the importance of being able to draw free-body diagrams and determine loads. Clearly, if the loading on a part cannot be properly determined, the consequent design analysis is meaningless. Section 1-4 presents the idea of being able to visualize the flow of force through a machine part, a technique that is invaluable for identifying the locations of maximum stresses. Section 1-7 emphasizes the relative strengths of stress patterns, and Section 1-10 reviews St. Venant's principle and demonstrates how rapidly even a knife edge load distribution will spread and become an almost uniform load distribution.

Chapter 2 studies in detail the efficient stress patterns of tension, compression, and uniform shear and discusses the inefficient stress patterns of bending, transverse shear stress, and spot contact.

Chapter 3 reviews the concept of a spring constant and then demonstrates that the efficient stress patterns are related to rigidity and that the inefficient stress patterns are related to flexibility. Section 3-5 gives design recommendations for increasing the rigidity of machine and structural parts. Designing for uniform stress produces rigid parts.

Chapter 4 presents the general principle for form design, which is "design for uniform stress." The principles that follow from the general principle are presented in Sections 4-2 to 4-6: tetrahedron-triangle; uniform shear or hollow shaft; forcing load; mating surface; and load-lever principle. Once understood, these principles are easy to apply in the design synthesis process.

Chapter 5 discusses tension, compression, and bending. Section 5-4 reveals configurations that are highly efficient strength-to-weight ratio shapes for bending. Section 5-5 points out the merits of the sandwich construction for use in resisting bending moments.

Chapter 6 shows how the membrane analogy can be used in designing parts loaded in torsion. Studied are the relative strength of circular vs. noncircular cross-sectional shapes, inward vs. outward protruding corners, and closed vs. open cross sections.

Chapter 7 presents a study of contact stresses. Section 7-1 begins with a discussion of Hertz equations for the general case of contact between two elastic bodies. Section 7-2 looks at contact stresses in parallel cylinders. Section 7-3 discusses material methods useful for determining contact stresses for both Hertzian and conformal contact. Section 7-4 studies contact stresses in indented strips and slabs, and Section 7-5 presents work done by Peter Engel at IBM on contact stresses in type characters. The remaining sections of Chapter 7 look at gear tooth form optimization to reduce wear and contact stresses as well as press fit shaft parts.

Chapter 8 presents buckling conceptually as a shift from an efficient to an inefficient stress pattern. For example, in column buckling there is a shift from compression to bending. Section 8-2 looks at buckling in components. Section 8-3 gives critical lengths of members for buckling by compression and torsion. The remaining sections present methods for preventing buckling and discuss the design of lightweight frames.

Chapter 9 presents the analysis for axial and torsional impact using the energy method. The energy absorbing ability is greatest for parts stressed uniformly throughout. Efficient stress patterns are preferred to inefficient patterns. Ideas are presented for improving the impact design of components. Design considerations are given for minimizing the effects of impact loads.

Chapters 10 and 11 deal with the design of joint elements. Joints can be thought of as breaks in the continuity of machines or structures. Joints are needed to efficiently manufacture and assemble machines. Principles are presented for part design and for increasing the strength-to-weight ratio efficiency of joints.

Additional principles are presented for increasing body and joint efficiency in Chapter 12. Discussed are the use of supplementary structural shapes, floating or semifloating parts, and the elastic matching and the shape refinement principles.

The final chapter, Chapter 13, presents the principle of relative stiffness. Several examples to illustrate the principle are presented: (1) load distribution in modular belting; (2) load in a three-column concrete structure; and (3) load distribution in chains and sprockets, timing belts, and threaded connectors. Also presented is a discussion of the load shift phenomenon.

The principles presented in this book are important, but they will not be sufficient to solve a complete engineering problem. It is expected that a thorough understanding of the ideas presented will guide the reader in producing well-formed machine and structural parts, components, and structures. The engineering know-how, ingenuity, insight, and imagination acquired through many years of engineering experience can be supplemented with the principles presented. Although computer power has increased and costs have decreased drastically, the understanding of the principles of form design will reduce the time and expense in producing efficient designs.

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August 1987

ACKNOWLEDGMENTS

This book evolved at the beginning from classroom outlines developed by Professor Walter L. Starkey of The Ohio State University, under whom I studied over 15 years ago. My interest in the area of mechanical engineering design was influenced by the fact that I studied this field under Professor Starkey, an outstanding engineer, teacher, and gentleman whom I very much admire. Professor Starkey's classes were an introduction to a totally different way of thinking on problems ranging from design to assessing the value of free speech. (I would also be amiss if I did not mention the influence of studying Strength of Materials under Professor Ralph I. Stephens while he was teaching at the University of Wisconsin.)

After graduate study at Ohio State, I introduced the principles of form design into the design classes at The University of Connecticut. Unknown to me at the time, Professor Terry E. Shoup, a classmate of mine at Ohio State, was doing the same at Rutgers University. In 1976, we both had joined the faculty at the University of Houston, and there decided to develop and teach a short course covering the principles of form design.

Not being able to interest Professor Starkey nor Professor Shoup in writing a form design book, in 1981 I decided to undertake the task myself. Fortunately, I have had help from numerous students: David Tso, Shiran Nanayakkara, Hsien-Heng Chen, Raul Longoria, Monica Gonzalez, and Srikanth Kannapan. My goal was to simply present and illustrate, in the most efficient manner, the concepts of form design.

To rephrase the words of Professor Robert Juvinall:* "While every effort has been made to insure the accuracy and the conformity with good engineering practice of the material in this book, there is no guarantee, stated or implied, that machines or structural parts designed based on the information provided in this text will be in all cases proper and safe. Design is sufficiently complex that its actual practice should always take advantage of the literature in a specific area involved, the background of experience, and most important, appropriate experiments to verify proper and safe performance."

*Juvinall, R. C., **Fundamentals of Machine Component Design,** John Wiley & Sons, New York, 1983.

CONTENTS

1

INTRODUCTION TO FORM DESIGN

Machines and structures are monolithic assemblages comprised of body and joint elements. Generally, when a body or joint is subjected to loads, efficient and inefficient stress patterns are introduced. The problem is to be able to recognize what forms and shapes cause which stress patterns and to apply this information to produce an improved design.

1-1 GIVEN INFORMATION

The designer usually has a definition of the problem that must be solved as well as knowledge of the design considerations listed in Table 1-1 before beginning to synthesize the size and shape of a machine or structural part. The designer generally needs to know: (1) the *performance* requirements—the magnitude and location of the applied forces and the motions of the part; (2) the required *life;* (3) the *cost* involved in producing or purchasing the part; and (4) the *constraints*—space, weight, fabrication, materials, aesthetics, compatibility with other parts, and compatibility with the environment.

The information needed, for example, to select chain and sprocket size and shape for a drive system is the (1) power to be transmitted, (2) angular speed of the driven shaft, (3) desired speed ratio, (4) source and type of power, (5) available space for the drive, (6) shaft diameters, (7) type of equipment to be driven, (8) operating environment, and (9) desired life of the installation.

TABLE 1-1. Design Considerations

1. Capacity (power, load, thermal)
2. Motion (kinematics, vibration, dynamics, controllability)
3. Interfaces (appearance, space limits, load type(s), environmental compatibility)
4. Cost (initial, operating)
5. Life
6. Reliability
7. Safety
8. Noise
9. Availability of components
10. Producibility
11. Maintainability
12. Geometry (size, shape)
13. Rigidity
14. Elastic stability (buckling)
15. Weight
16. Materials (strength, cost, availability, modulus of elasticity, toughness)
17. Uncertainties (load, environment, cost, material)

1-2 MACHINE ASSEMBLAGE

A machine consists of an assemblage of monolithic parts, each of which, in general, has a *body* and several *joint* elements. Figure 1-1 identifies joint and body elements in a chain-drive system. Figure 1-2 shows joint and body elements for a channel beam whose ends are welded onto immovable supports.

1-3 FREE-BODY DIAGRAMS

A body that is composed of one or several components can be analyzed by separating it into parts. The behavior of each portion of the body can then be isolated and studied. When a portion is removed from the rest of the body, the internal

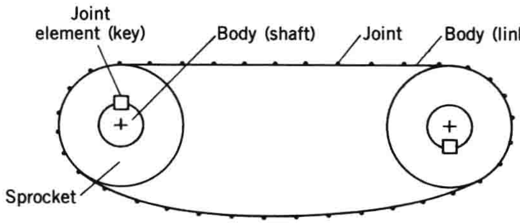

FIGURE 1-1. Chain-sprocket drive system showing body and joint elements.

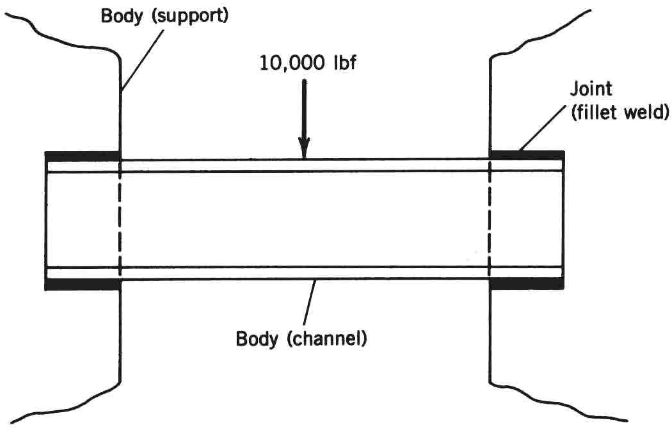

FIGURE 1-2. Channel beam welded at ends and loaded in the middle.

forces and moments that exist at the boundary between the removed and remaining portions of the body are redefined as external forces and moments (see Fig. 1-3). Diagrams of bodies or body portions are called free-body diagrams. More specifically, a *free-body diagram* is a drawing or a sketch of a body (or part of a body) that shows all the forces from the surroundings acting on that body. The forces could be caused by gravitational attraction, centrifugal acceleration, magnetic repulsion or attraction, or another body.

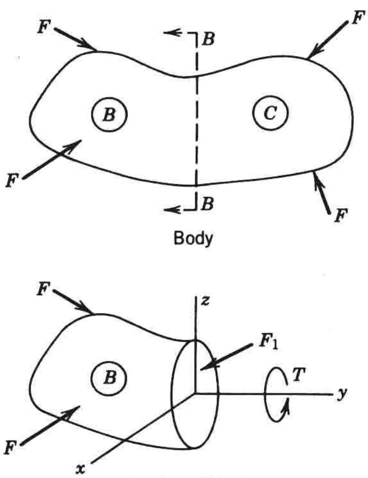

FIGURE 1-3. Construction of a free-body diagram