Chapter I
Introduction to Engineering Design

Introduction

Furniture is one of man’s most prized possessions. He sits on it, sleeps on it, eats on it, and perhaps most importantly, puts his most valuable belongings into it. It is noteworthy that at an early age in recorded history, man had already developed furniture designs and constructions which differ little from those in use today. Chairs, cabinets, and even a folding bed, for example, found in King Tutankhamen’s tomb (Desroches-Noblecourt, 1963) closely resemble their modern counterparts. Furthermore, joints that are still widely used such as mortise and tenon joints were also known and used over 3000 years ago. In spite of its ancient history, little is known about the science of furniture construction, or, as it will be termed here, the engineering design of furniture. The design of furniture, like that of most structures of historical origin, evolved through experience gained by trial and error. But whereas analytical procedures have been developed and incorporated into the design of other structures, they have not been systematically introduced into the design of furniture.

Several reasons can be cited why the scientific design of furniture has received so little attention. The most likely reason is that because safety and minimum material weight considerations have seldom been of overriding concern, an impetus to introduce scientifically based analytical concepts has largely been lacking. Without need there as been little motivation for furniture-oriented structural research, and, as a result, little or none of the detailed information needed in the analytical design of furniture has been determined. In contrast, this information has been developed for other structures such as bridges and buildings through years of persistent, painstaking effort by thousands of researchers. Results of both trial and error methods and systematic scientific research have led to numerous product improvements and often to the establishment of construction standards which have resulted in numerous benefits to society. Today, for example, an individual can cross a bridge, fly in an airplane, or enter a public building with confidence that each of these structures has been designed and built in accordance with strict engineering regulations that have been developed to ensure the safety of the occupants. Furthermore, refinements in engineering design procedures have made possible the use of structures with narrower margins of safety but with ever greater designer-specified reliability. These refinements have led to economic savings and have also made possible otherwise impossible undertakings such as the exploration of space.

In the case of furniture, however, initial purchase price and the manufacturer’s reputation remain the principal criteria used to judge its
structural quality. There is, of course, no good reason why this should be so. A structurally sound chair can just as well be made of pine as of walnut and cost certainly need not be the only indicator of quality. Engineering design provides the tools needed for manufacturers to construct structurally sound furniture at any price level and the information required for consumers to buy furniture specifically designed to meet their usage requirements.

Types Of Design

There are three separate yet closely related areas of design which must be considered in the creation of a new piece of furniture. The first, and in the case of furniture, the most important area is that of esthetic design, that is, the artistic development of a structural form that is appealing to consumers and which will culturally enrich their lives. The second area is that of functional design, that is, the planning of the structure so that it will perform its intended function in as efficient manner as possible. The third and final area is that of engineering design, that is, the planning of the structure so that it can safely resist the loads imposed upon it in service.

A consideration of esthetic and functional design principles is beyond the scope of this paper. It should be noted, however, that the esthetic design of a piece of furniture in most cases will dominate all other factors. Whenever possible, conflicts between engineering requirements and esthetic considerations should be resolved in such a way as to leave the artistic design unaltered. Functional design concepts, in contrast, ordinarily receive much less attention. Yet, in many cases, the correct functional design of a piece of furniture is even more important than either the esthetic or engineering design. As man becomes more sedentary and spends more time sitting or reclining, and as space and materials become more scarce, this subject becomes ever more important.

Until recently, the scientific or engineering design of furniture also received little attention. Consumer demands for more reliable products, government pressures for warranties of furniture, increasing needs for material economics, and a scarcity of skilled craftsmen who can intuitively create furniture that is structurally sound, however, have all combined to make this subject one of growing importance. This book is accordingly devoted to this subject—the engineering design of furniture.

Engineering Design Principles

Although the phrase, "engineering design of furniture," is commonly used, its meaning is not always fully understood. Essentially, the engineering design of a piece of furniture, just as that of any other structure, consists of carrying out the following procedure: First, determine the loads which will act upon the structure in service. Second, estimate the sizes of the members or parts required to carry these loads and "draw up" a "trial" structure. Third, analyze the magnitude and distribution of internal forces which arise in this trial structure under the
action of the external loads. Fourth, if necessary, redesign the trial structure and repeat steps two through four until no part is over-stressed. Fifth, design the joints so that they can safely carry the internal forces and external loads which will act upon them in service. In contrast to trial and error methods, this procedure provides a methodical way of designing a piece of furniture to meet any specified service condition.

Loads

Logically enough, the first step in this design procedure consists of determining the loads which the piece of furniture must be able to withstand in service. Such loads are not always predictable and frequently their determination is more difficult than the design of the structure itself. In order to select these loads, the designer must have a thorough knowledge of the conditions the furniture will encounter in service. He must know not only how it is used but also how it is abused. Specifically, he needs to know the nature of the forces that will be encountered, whether they are static or dynamic, their magnitude, and their direction and frequency of occurrence. In the case of sofas, for example, he needs to know the forces that arise when users sit down, lean backward, and then move around as they settle themselves. He also needs to know what forces are imposed on the sofas when they are transported and when they are moved. Such forces may be quite high and much furniture is damaged in transit. He also needs to know whether the sofas will be shoved across a floor or whether they will be lifted and carried from one location to the next. If they are to be transported for any distance, he needs to know whether they will be moved in an upright position or standing on end. Obviously, it is important that as many potential uses of the furniture as possible be anticipated. Many failures occur in service simply because the ways in which the furniture was used were not foreseen.

Similarly, in other areas, a designer must know, for example, what are the loads imposed on a chair when a person sits down on it, leans back, twists around, and so on, and how frequently do these loads occur? What is the weight of the dishes you can put in a kitchen cabinet or the books on a bookshelf? How heavily can you load a table and how hard can you push against it sideways? How much paper can you put in a drawer, or nuts and bolts as the case may be? Must a bed support only the weight of the people sleeping on it, or will it also see occasional service as a trampoline for the youngsters in the family? These considerations are typical of the service factors that must be considered when designing a piece of furniture.

Trial Structure

The second step consists of drawing up or creating a hypothetical trial structure that it is expected can safely carry the loads that have been decided upon. In the case of furniture, the trial structure is usually the designer's sketch of the proposed piece of furniture. Considerable judgement must usually be exercised in developing this construction.
Theoretically, members of almost any cross section could be used in drawing up trial structures, but in the interest of efficiency, it is desirable that the first estimates be reasonably close to the final required sizes. Intuition, experience, and good judgment are all useful tools in formulating such estimates. Close estimates are not required, but they do help to shorten the design process.

In estimating member sizes, both the forces acting on the members and the mechanical properties of the materials of construction such as ultimate strength, impact resistance, fatigue resistance, and resistance to creep must be taken into consideration. It is also important that the piece-to-piece variation in strength properties of the material selected be known. Furthermore, the construction of the joints also must be considered since the sizes of the attached members may not permit the construction of joints of sufficient size—and, therefore, strength—to carry the loads imposed on them.

**Member Design**

Once the initial member sizes for the trial structure have been selected, the structure is then analyzed mathematically to determine the magnitude of the internal forces acting on the members and joints and also to determine the deflections of the various parts. Two problems are involved. First, mathematical models must be available that faithfully reflect the behavioral characteristics of the real structure, and secondly, methods must be available for carrying out the calculations involved both rapidly and economically. It must be understood that an actual structure is not analyzed as such but rather an idealized representation of it that can be treated mathematically; that is a mathematical model. Obviously, the results of an analysis are only as good as the model used. "Good" models do not necessarily exist for all types of furniture, and unfortunately, there are few shortcuts which can be substituted for research and testing in developing them.

The problems involved in the analysis of a piece of furniture are often both technically difficult and computationally quite complex—even more so than those ordinarily encountered in the analysis of more conventional structures. Members in a furniture frame are often curved and of non-uniform cross section. Joints are usually flexible rather than rigid, and they often distort under load in a non-linear manner. They are also of such size relative to the members that they join together that their dimensions and their effect on the analysis cannot be ignored. Furthermore, the geometry of the total structure is such that planar representations of it frequently cannot be made, and the frame must be designed as a three-dimensional structure. Simplifications made in the analysis of textbook problems, therefore, often cannot be used in the analysis of real furniture frames.

This has been an important factor in delaying the introduction of rational strength design concepts into the product engineering of furniture.
construction. Until the introduction of large high speed digital computers, the analysis of many types of furniture frames was, in fact, largely impractical because of the overwhelming volume of tedious calculations required. Today, however, computer-based methods of analysis have been developed which make it possible to carry out analyses both quickly and economically on desk top personal computers.

After the initial analysis has been completed, each member of the trial structure is examined to determine whether it has been properly designed to resist the forces imposed upon it. In some cases members may be too small, whereas in other cases they may be too large. In either case, appropriate changes are made in the member sizes, and the modified trial structure is again analyzed. This procedure is repeated as often as is needed to determine the appropriate sizes for the members. Any member may be over-designed if desired, of course, which may be desirable for artistic or other reasons. The important point here is that an analysis of the proposed structure provides the information that is needed to determine exactly how highly each member or part is stressed, and also to determine the forces acting on the joint.

Sizing of members is based upon a consideration of the strength and stiffness properties of the materials from which they are constructed. The stiffness properties of most of the wood-based materials used in furniture construction are known (Eckelman, 1978; USDA, 1987). Allowable stress design values for these materials as they are used in furniture have not been adequately established, however, so that uncertainties still exist in setting reasonable design levels. Expected variations in strength of the material itself are of particular concern. In particular, the least strength which can be expected from the material at a specified percentage of the time must be known so that stresses can be set at a level that will permit construction of a structure that has enough strength to hold up in service with a reasonable factor of safety but yet does not contain so much material as to be uneconomical to build.

Design of Joints

The final and certainly one of the most important steps in the strength design process consists of designing the joints. This step is carried out only after the final sizes of all the members have been determined so that the forces acting on each joint are accurately known. Traditionally, joints have always been the weakest part of a piece of furniture. It is probably safe to say that more furniture has failed because of weak joints than from any other single cause. There is also probably less known about the design of joints than about any other part of a piece of furniture. This statement is not meant to imply that furniture joints have not been studied or researched, because a substantial amount of work has in fact been done in this field. Most of these investigations have been qualitative in nature, however, rather than quantitative. They have dealt with how to build "better" or "stronger" joints or have been concerned
with the effect of a specific parameter on joint quality rather than how to construct joints with specified strength. As engineering techniques have entered into furniture design, the need for quantitative values has begun to change this situation somewhat, and information is now available that can be used to design certain types of furniture joints. There is still a great amount of research that remains to be done in this area, however.

State Of Furniture Engineering

The strength design process, as a part of product engineering, provides a rational means of designing furniture to meet any specified service condition. This process is of interest to consumers as well as to manufacturers because once the service requirements of an installation have been established, furniture can be produced that has been designed to meet these specific needs. At this time, the information required to design furniture on an exact scientific basis is still too imperfect to rely totally on strength design methods. Numerous unresolved questions remain, and furniture engineering must still be regarded as much an art as it is a science. Considerable progress has been made in certain areas, however, particularly in those areas that deal with the analysis of furniture frames and cases. Significant advancements have also been made in the rational design of joints. Because of these developments, it is now possible to engineer several types of furniture on a rational basis. In addition, performance tests are now available to support the basic engineering design process. Hence, the product engineer now has two powerful tools available to supplement judgement and experience in designing efficient furniture constructions and to help disclose and avoid those constructions that are likely to cause difficulties in service.

The most significant problems that remain unsolved are those that deal with service loads, allowable design values for the materials of construction, and joint design information. There is a growing body of research that is relevant to these problems as well as to structural analysis, however, and new solutions are constantly appearing. Unfortunately, most of this data is scattered throughout the literature, and much of it, therefore, is not readily available. One of the purposes of this book is to collect and summarize the information that is pertinent to furniture design into a single document and thereby make it readily available to designers and manufacturers.

References


Appendix

General Comments On Engineering Design

Engineering design is not a pure science in the same sense that mathematics is a pure science. Rather, it is a discipline that combines both art and science. The science of engineering design is that part of it that deals with exact and rational relationships. The analysis of the "trial" structure, for example, is exact and rational. It is based upon mathematical concepts and, for a given set of conditions, will always give the same answer. It should be realized, however, that an actual structure is never analyzed but rather an idealized model that represents it. Because the behavioral characteristics of a real structure are seldom completely known, simplifying assumptions are made in the model that reflect these uncertainties. As an example, in simple or determinate structures, members are often assumed to be weightless, joints completely free to rotate, and so on (Shedd and Vawter, 1941). None of these conditions exists perfectly in the structure, but as long as the characteristics of the idealized structure do not differ too greatly from the real structure, an analysis of the former will apply sufficiently well to the latter for all but the most exacting purposes.

In the case of more complex indeterminate structures, the analysis is based upon a consideration of the deformations that the members and the structure as a whole undergo. External and internal forces must not only be in equilibrium, but they must also result in consistent elastic deformations (Parcel and Moorman, 1955). The analysis of an indeterminate structure thus requires previous knowledge of the deformations that take place within the real structure, and the applicability of the analysis to the real structure rests on sound engineering judgment and experimental verification. An analysis of a structure whose strain characteristics are assumed without experimental verification may be mathematically correct with respect to the model used but considerably in error with regard to the actual structure. It is very important, therefore, that a model faithfully reflects the behavioral characteristics of the real structure it represents. It should be evident here that the selection of an appropriate model is largely a matter of judgment. It involves a resolution of factors that are not completely known about the structure, based upon judgment, experience, and experiment in order to obtain a solution to the problem. This ability to cope with uncertainties, with situations where exact relationships have not been established, is termed the art of
engineering.