PRODUCT ENGINEERING AND PERFORMANCE TESTING IN RELATION TO STRENGTH DESIGN OF FURNITURE

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ABSTRACT

This article contains a narrative description of the history, current status, and possible future progress of the product engineering, strength design, and performance testing of furniture. Product engineering is covered both in general and from a furniture perspective. Strength design of furniture forms the essential part of the article.

Reliability concepts are depicted in general both in their application to furniture and in their incorporation into standards for performance testing. The major objective of reliability and performance testing is to improve the durability and safety of furniture products and to predict failure or unexpected problems associated with them.

Testing and evaluation are needed to obtain safe and reliable furniture and should provide pertinent expected performance information to manufacturers and customers alike. Both the history of development of strength design and its current stage of development are treated, along with suggestions for its use in improvement of furniture construction. In conclusion, an integrated methodology for the production of high strength furniture in view of current technological improvements is outlined.

Keywords: Furniture, strength design, performance testing, product engineering.

PRODUCT ENGINEERING IN GENERAL

Engineering, by definition, is the application of a systematic, disciplined, quantifiable approach to the design of structures, machines, products, systems, or processes. Product engineering can be defined as the generation or development of a product using scientific tools and methods under the influence of certain physical and mechanical constraints or guidelines.

Furniture is often considered as a work of art, while the engineering aspects of furniture such as structural durability often are considered to be of secondary importance. However, as in many other fields, product engineering is essential to the field of furniture. The most important aspect of product engineering of furniture is structural

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design. Often, however, aesthetic needs are favored over the structural requirements of the products. Even though, in general, fashion sells furniture, a methodical design approach should be applied that generates structurally sound, safe, and durable furniture.

Rational strength design of furniture is a relatively new concept. Until the mid-1950s, furniture had not been investigated structurally in spite of the fact that all new furniture is some type of structure. Naturally, furniture has some features that require special scientific consideration. However, the principles of structural mechanics can be applied as they are applied to any other engineered structure.

Although simple in appearance, most furniture frames are structurally quite complex. Usually, they are statically indeterminate; their members are often curved and of non-constant cross section. These factors decidedly complicate the execution of an analysis. Since engineering design includes an analysis of the behavior of individual fasteners and joints in the structure, specific connector problems must also be investigated and defined during the development procedure (Eckelman 1968).

Kotas (1957, 1958a,b) was one of the first scientists to treat furniture as an engineering structure. He made theoretical and experimental analyses of cabinet structures. He also undertook some studies about the stiffness of case furniture. He treated furniture joints as semi-rigid joints in theory. He also deduced that joints act elastically, so the higher the modulus of elasticity (MOE) of the joint, the less it deforms.

Hart (1965) pointed out some structural aspects of furniture design. He claimed that, in designing furniture, consideration must be given not only to its appearance and function, or fitness for purpose, but also its strength and rigidity. He briefly outlined relevant structural principles and illustrated their use in the design of certain pieces of furniture such as chairs and cabinets.

Hindsley (1968) dealt with the design of chairs. He indicated that the first essential element in designing any framework is to consider what loads it may be called upon to bear so that the designer may make it adequately strong. He divided the loads on chairs into three classes, functional, non-functional, and dynamic. Even though Hindsley made this load classification for chairs, it could be applied to any other furniture structure.

Eckelman (1968) developed a computer-based analytical design system for furniture frames with elastically nonlinear, semi-rigid joints. He used stiffness matrix structural analyses in his study and wrote a computer algorithm in FORTRAN programming language to facilitate execution of the analytical procedure. He compared the test results of representative frames with computer-based results and concluded that the analytical techniques developed were valid and that a furniture frame could indeed be designed according to engineering principles.

Lin and Eckelman (1987) indicated that although expressions had been developed to predict the deflection of five-sided cases, these expressions do not take into account the stiffness of the joints. They evaluated the effect of joint rigidity on case stiffness. Results of the study showed that joints do have significant effect on cases stiffness, and manufacturers may want to use joints that provide the greatest stiffness in their constructions. In a similar study, Eckelman and Munz (1987) provided a procedure for calculating the stiffness of the cases that contain front frames. In a further study, they provided a method for evaluating the effect of joint stiffness on overall case stiffness.

Gustaffson (1995; 1996a,b; 1997a,b) used finite element methods (FEM) to analyze chairs constructed with some Swedish wood species, and Smardzewski (1998) developed a computer program to analyze furniture side frame constructions. Results of his case study on chair side frames indicated that the computer program developed allows accurate, rapid, and multiple rigidity/strength analysis of furniture side frames constructed of wood.

In their recent research, Kasal and Pullela (1995) developed analytical models for structural analysis of furniture frames by finite element methods. They collected the stiffness and the load-deformation characteristics of joints by experiment, and then incorporated the results into the input for the analysis models. They concluded that the analytical models provided useful reliable information concerning the deformations and internal forces acting on a piece of furniture in service. In this study, ANSYS Parametric Design Language (APDL) was used to build the analytical models.

A recent study (Kovacs and Orban 1999), introduces a suggestion for an engineering design concept, pointing out questions of level of reliability, design stress values, structural modeling, and computations by means of finite element analysis methods and joint design. In this study it was pointed out that research done globally in the area of strength design of furniture should be summarized and integrated to produce a "code of practice." Presumably "code of practice" means a manual that specifies the outlines of strength design of furniture by combining the background methodology and tools with today's technology-driven methodology and tools.

RELIABILITY AND PERFORMANCE TESTING

The idea of reliability, i.e., the ability of a piece of equipment or product to perform a required function under stated conditions for a stated period of time, is an integral part of the product engineering process. The objective of reliability is to improve the durability and safety of the product and thereby forestall the unexpected serious consequences of failure. One way, if not the most important one, of designing and producing reliable products is to test the performance of the product under actual or simulated conditions (Smith 1980).

The main purpose of reliability is to obtain information regarding failures, in particular, the tendency of the product/equipment to fail as well as the consequences of such failures. In the design and development of the products, the first prototypes usually contain various design and engineering-related deficiencies. In fact, according to Benton and Crow (1989), the reliability of a new design product/system could be very low, i.e., 15 to 50% of the mature design capacity.

Performance testing should be an integral part of the product engineering of furniture. Performance tests, from a furniture point of view, are defined as "accelerated use tests that predict the ability of furniture to fulfill its intended function." These tests are powerful analytical tools that can be used to eliminate many of the hazards and uncertainties associated with the development of furniture (Eckelman 1988a). The main goals of a successful test are (a) to provide quantitative feedback to the designers to make improvements in the structure, (b) figure out problems that were overlooked in design but can be encountered in service, and (c) verify that the product is fit for its intended use. Performance testing provides the last feedback opportunity in the furniture engineering process before furniture goes into service, and therefore provides the last opportunity for increasing the quality and reliability of furniture.

Eckelman also indicates that in order to develop universally accepted performance tests, test methods should be independent of geographical range of applications and provide a maximum amount of engineering design information. These test methods should provide manufacturers with the information needed to market their products and consumers with the information needed to evaluate them. Furthermore, they should provide a means of quantifying historical field experience and a means for quantifying the strength of furniture in an explicit manner.

According to Eckelman (1988a), in developing performance tests for furniture, the following procedure is typical: Observe how the furniture is used in service; obtain reasonable estimates of the loads applied and their frequency of occurrence; based on the observations, develop a test method that simulates user service actions.

During the course of its service life, furniture is subjected to repeated normal load applications, along with occasional chance abusive loadings. While the furniture is relatively new and retains a high degree of its initial strength, it is able to resist these loads. As its strength decreases with time, however, a point is reached when the magnitude of overload exceeds its residual strength, and the furniture fails (Eckelman 1988b).

Eckelman (1988b) defined this sequence of events as a "first-crossing" concept of failure (Fig. 1) that is based largely on a cumulative damage theory. In essence, it is postulated that each time furniture is subjected to a load, it is slightly damaged by this action and thereby slightly weakened. When it is new, the furniture retains a high degree of its initial strength, and is able to resist both normal and "abusive" abnormal loadings. With time and use, the strength (or resistance) of the parts and joints diminishes, and eventually a point is reached when an applied load, often an abusive load, is greater than the residual resistance of the construction. At this point, a first-crossing occurs, i.e., the load applied to the furniture exceeds its strength and failure occurs.

It would be difficult to incorporate a first-crossing concept totally into a simple test method for furniture, primarily because the load/use spectrum for furniture is not known, and appropriate load models have not been developed. Also it would be somewhat difficult to introduce a complex service loads spectrum into the loading sequence using simple equipment (although, this can, in fact, readily be done with a process controller linked to a computer). A compromise method that satisfies several of the desired requirements of the first-crossing concept may be described as the "cyclic stepped load" method (Fig. 2). In this method, a given

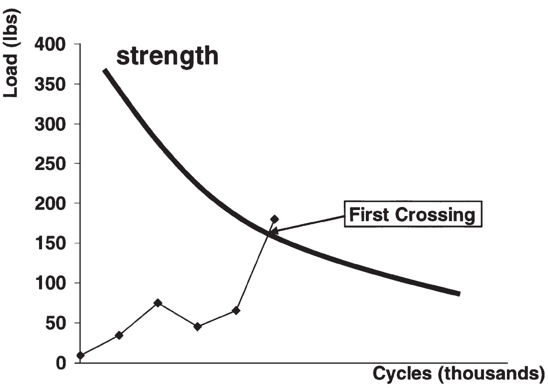

FIG. 1. First-crossing concept.

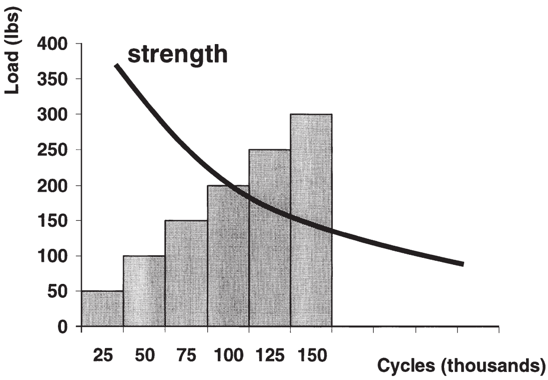

FIG. 2. Cyclic stepped increasing load concept.

load is applied to the furniture at a given cyclic rate for a specified number of cycles. After the prescribed number of cycles has been completed, the load level is increased by a given increment, and the procedure is repeated. This process is continued until a desired load level has been reached, or until the furniture fails.

This method of test involves an interaction between (a) initial starting load, (b) load increment, (c) number of cycles at each load level, and (d) total number of cycles. Its greatest value lies in the fact that parameters can be adjusted to give conditions that range from essentially a static load test to a fatigue test. Furthermore, simply by changing the load-step increments, the sensitivity of the test can be adjusted readily to detect the performance differences of any desired magnitude between two pieces of furniture.

The critical parameters that must be established for a method of test based on this process are (a) the cyclic load rate, (b) the initial starting load, (c) the load increments, and (d) the number of cycles to be completed at each load level. To a certain extent, these values are arbitrary, but experience quickly delineates the limits of their range. Most furniture cannot be tested at a cyclic rate greater than 20 cycles per minute without introducing secondary structural vibrations. More importantly, with pneumatic systems, delivery of the air at higher rates is complex. On the other hand, if a hydraulic system is used, rates over 20 cycles per minute could be reached, but the stroke of each cycle would be reduced. In testing furniture, large amounts of deflections can be observed even before the construction fails. Hence, a pneumatic system that allows long strokes on each cycle is needed. Therefore, a rate of 20 cycles per min may be considered as a reasonable rate for performance testing of furniture. Initial starting load should be low enough to allow completion of cycling at several load levels. Load increments should be small enough to detect difference in performance. The number of cycles to be carried out at each load level is less easily defined. Certainly, it would be difficult to defend the use of any specific number of cycles on the basis of strict scientific reasoning. Hence a heuristic process must be coupled with a degree of practicality in order to arrive at an optimum value. Extensive structural testing tends to indicate that furniture should be subjected to about 25,000 test cycles at each load level. This is a convenient value since it requires approximately 21 h to complete 25,000 cycles at a rate of 20 cycles per min. Use of cyclic rate of 20 cycles per min, therefore, enables a test to be completed at one load level and the rest restarted at the next load level every 24 h—provided that the equipment is developed in such a way that the test can be left to run unattended (Eckelman 1988b).

A multipurpose universal structural performance test method that can be incorporated into the product engineering process was introduced in the late 1980s by Eckelman (1988b). The comprehensive techniques of the test were applicable to many kinds of furniture such as chairs, tables, sofas, office chairs, and cabinets. Subsequently, the test method was used to evaluate the strength of library chairs and tables (Eckelman 1977, 1982), and chairs for air traffic controllers (Eckelman 1979). The method was also incorporated into standard testing of upholstered furniture and intensive use chairs (Eckelman 1978a,b, 1985; GSA 1981).

CONCLUSIONS

Performance testing is an important means of experimentally verifying that product development procedures work as intended. The main goals of a successful test are (a) to verify that the product is fit for its intended use, (b) to figure out problems that were overlooked in design but can be encountered in service, and (c) to provide quantitative feedback to the designers to make improvements in the structure. In other words, performance testing provides the feedback in the furniture engineering process before furniture goes into service, and therefore provides the last opportunity for increasing the quality and reliability of furniture.

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