RELIABILITY ANALYSIS AND ASSESSMENT OF STRUCTURAL SYSTEMS

J. T. P. YAO

Department of Civil Engineering, Purdue University, West Lafayette, Indiana 47907, U.S.A.

C. A. ANDERSON

Group R4, Reactor Technology, Los Alamos Scientific Laboratory,
Los Alamos, New Mexico 87545, U.S.A.

SUMMARY

The study of structural reliability deals with the probability of having satisfactory performance of the structure under consideration within any specific time period. To pursue this study, it is necessary to apply available knowledge and methodology in structural analysis (including dynamics) and design, behavior of materials and structures, experimental mechanics, and the theory of probability and statistics. In addition, various severe loading phenomena such as strong motion earthquakes and wind storms are important considerations. For three decades now, much work has been done on reliability analysis of structures, and during this past decade, certain so-called "Level I" reliability-based design codes have been proposed and are in various stages of implementation. These contributions will be critically reviewed and summarized in this paper.

Because of the undesirable consequences resulting from the failure of nuclear structures, it is important and desirable to consider the structural reliability in the analysis and design of these structures. Moreover, after these nuclear structures are constructed, it is desirable for engineers to be able to assess the structural reliability periodically as well as immediately following the occurrence of severe loading conditions such as a strong-motion earthquake. During this past decade, increasing use has been made of techniques of system identification in structural engineering. On the basis of non-destructive test results, various methods have been developed to obtain an adequate mathematical model (such as the equations of motion with more realistic parameters) to represent the structural system. These mathematical models, with updated physical parameters, can then be used in a reliability analysis involving expected future loading conditions and thereby update the reliability estimates.

A method for assessing the reliability of existing structures is advanced in this paper. For virgin structures the use of periodically measured non-destructive test data (such as low level vibration response) and data from multiple tests carried out at different amplitudes can be used to assess the reliability of the structure to expected future severe loading conditions. In addition, test data obtained after a structure has been subjected to a severe loading condition can be used to assess the reliability of the structure to further severe loading conditions. Application of the proposed method to the assessment of the reliability of a typical nuclear structure will be made.

Finally, it is suggested that these updated reliability estimates can be used to guide maintenance programs for existing nuclear structures.

1. Introduction

At present, structural analysis usually deals with idealized structural models. The most sophisticated models include certain nonlinearity effects as well as complex structural elements, and analysis of such models can be obtained with numerical techniques and the use of large computers. Nevertheless, most existing structures are still too complicated to be precisely modeled. Consequently, various studies have been made to identify the imporant characteristics of existing structures, and these studies belong to a subject area called "structural identification" [1-5].

In most of these structural identification studies, a mathematical model with unknown parameters is assumed to represent the structural system; for example, lumped-mass models are frequently used. Responses (output) of the real structure to known forcing functions (input) are recorded, and the recorded input-output data are then used to estimate the unknown parameters in the assumed mathematical model. Although the resulting representation for the structure is still an idealized model, it is a more realistic one because of its estimated parameters resulting from actual test data. Further analyses of this structure involving expected loading conditions can then be made using such a mathematical model.

During the past three decades [6] much progress has been made in the theory and application of structural reliability [7-10]. At one end of the spectrum, various approaches have been proposed to formulate the so-called Level I reliability-based design codes [10-14], which resemble current codes with relatively simple design formulas. At the other end of the spectrum, the state-of-the-art approach includes the application of random processes [15-18], risk analysis [19-21], and optimum design of structures [22,23]. These advanced studies add a new dimension to the practice of structural engineering in treating natural phenomena involving various degrees of uncertainty. Once again, most of the investigations conducted to date deal with idealized mathematical models. In 1975, Galambos and Yao [24] pointed out the need for more experimental work in developing new design codes.

All the mathematical analyses and experimental investigations prior to the construction of structures are certainly necessary, and continuing research and development in these areas is desirable. On the other hand, there exists a need to periodically analyze and assess the reliability of certain structures that have already been built and that can be subjected to hazardous loading conditions such as strong motion earthquakes and extreme winds. Such is the case of nuclear structures where loss of structural integrity can lead to dire public consequences.

The objectives of this paper are to:

(a) formulate the problem of assessing the reliability of existing structures,

(b) explore several possible approaches to the solution of this problem, and

(c) illustrate such methodologies with possible applications to nuclear structures.

It is hoped that this paper will serve to stimulate interest in this subject area.

2. Problem Statement

The reliability of a structure is denoted by $L_T(t)$ and is defined as the probability that the useful life, T, of the structure will be at least t, i.e.,

$$L_T(t) = P(T>t) \qquad (1)$$

Alternatively, this function can be expressed in terms of two random processes: namely, R(t) denoting the resistance (or capacity) of the structure, and S(t) denoting the applied force (or demand) on the structure as follows:

$$L_T(t) = P\,[\,R(\tau) > S(\tau);\ 0 \leq \tau \leq t\,] \tag{2}$$

If we let D(t) denote the damage of the structure at time t, the reliability function can also be given by:

$$L_T(t) = P\,[D(\tau) < 1;\ 0 \leq \tau \leq t]. \tag{3}$$

For structures undergoing no maintenance work, the reliability function thus defined is a non-increasing function of time t. The mathematical calculation of such a quantity in general can be very difficult indeed [25].

It is well known [7] that the reliability function can also be expressed in terms of the hazard (or risk) function, $h_T(t)$, defined as follows:

$$L_T(t) = L_T(0)\ \exp\,[-\int_0^t h_T(\tau)\ d\tau]. \tag{4}$$

Consider now the case of a specific structure. During its lifetime, several hazardous events occur as shown in Figure 1a. The corresponding hazard, damage, and reliability functions with and without maintenance and repair are indicated in Figures 1b, 1c, and 1d, respectively. The problem to be considered herein is the estimation (or assessment) of the quantities h(t), D(t), or $L_T(t)$ at the present time t, the results of which can be used to guide the decision whether major maintenance and repair work are needed for this particular structure.

3. Possible Approaches

A virgin structure immediately after completion of construction can be assumed to have an initial damage level (D_o) on some scale less than unity, which may be caused by poor workmanship, inferior quality of materials used, or accidental loading conditions during construction. On the other hand, the total collapse of a structure can correspond to a damage level of unity, which serves as the reference value on this damage scale. The damage of a structure can be indicated by

(a) visually observable physical changes such as can be indicated by initiation and propogation of cracks or progressive failure of structural components,

(b) directly measurable physical changes such as permanent or plastic deformations,

(c) changes in abstract structural characteristics such as the damping coefficients,

(d) change in mathematical modeling required to describe the behavior of the structure (e.g., the necessity of using nonlinear models for adequate representation indicates an advanced damage level).

Lacking a precise understanding and thus definition of structural damage, at present it is necessary to make use of as many of these damage indicators as is practical and economically feasible.

As is done in current practice, a structure can be tested with known forcing functions. Standard methods of system identification [26,27] can be used to estimate various structural parameters such as natural frequencies and damping coefficients. If several levels of the excitation are used, any detectable changes in each parameter can be considered a measure of damage in the structure at the time of testing. In this regard, the random decrement signature [28], which results from bandpass-filtering the time-history and then averaging all time segments at a given constant initial value, was recently applied for the detection of possible deterioration in bridge structures [29].

Because a high degree of nonlinearity in structural behavior usually corresponds to a high level of loading, another indicator for structural damage is the demarcation between linear and nonlinear structural models [30]. Recently, the Wiener technique of nonparametric identification has been applied to the case of earthquake response data of a reinforced concrete building [31,32]. Whether the second (or higher) order nonlinear kernel is needed for modeling purposes can be an indication of structural damage.

In the case of reversed loading conditions, cumulative fatique damage may result. This type of "damage" is also an abstract quantity, though evidence of its presence can be observed on the atomic or crystalline scale. Recently, large structural elements such as full-scale members and connections have been tested under reversed plastic deformation [33,34]. If the behavior of these full-scale specimens at various stages of damage can be "identified" with techniques available in system identification, a methodology may be established for estimating the damage level of existing structures.

4. An Application

If and when such a methodology can be developed for the assessment of damage and reliability of existing structures, applications can be made to various types of nuclear structures to insure their safety and serviceability. In the following, the core support of a High Temperature Gas Cooled Reactor (HTGR) is considered for the purpose of illustration.

The core of an HTGR consists of graphite blocks in the form of hexagonal prisms, which are set in closely packed columns to form a circular cylindrical core. The core is placed inside a relatively rigid Prestressed Concrete Reactor Vessel (PCRV), which supports the core laterally through a system of springs. Vertical support for the core is provided by graphite columns situated below the core that act as axial force members. The core measures approximately 11 meters in diameter by 9 meters in height and contains about 5000 graphite blocks. Reference [35] describes the HTGR core and supports in detail.

Reference [36] presents an evaluation of the structural integrity of the HTGR core support system and identifies those areas where additional supporting research is needed. Of particular concern are questions of the seismic behavior of the HTGR core on its support system and the statistical nature of graphite material properties - mainly its brittle fracture characteristics. In reference [37] the behavior of the core and its support system has been investigated in detail for both static (dead weight plus coolant pressure drop) and dynamic loading situations. It has been determined that for certain site conditions the horizontal earthquake component could cause sufficiently large torsional displacements between the core and PCRV that damage to the lateral spring support could result. In addition, the vertical earthquake component could violate the integrity of the support structure by inducing fracture in the support columns or in the column seats (by high local contact stresses). Therefore, a methodology for detecting damage in the HTGR structural support system following a strong motion earthquake could be very useful.

In the former case the damage can be indicated by a reduced stiffness and increased damping of the lateral spring supports. For the latter case measurement of differences in transit times of sound waves in the core support columns has been proposed as a means of detecting cracked or materially degraded columns. Such information would then be used, together with the available techniques of system identification, to update the reliability estimates of the core support system. However, further studies are needed to decide on the location(s) and type(s) of instrumentation as well as the source(s) and magnitude(s) of the forcing function. It is also necessary to establish criteria for damage thresholds so that rational decisions can be made as to when maintenance and repair work might be necessary or desirable.

In summary, a concept and possible methods for assessing the damage and reliability of existing structures are advanced in this paper. Much work is needed for the development and implementation of such a methodology. Nevertheless, the authors believe that it is timely to present these ideas for discussion purposes.

5. Acknowledgements

This approach to reliability assessment of existing structures was first discussed in a summary report by Yao [38] in June, 1976. Detailed discussion with Dr. S. C. Liu followed and his encouragement in this regard is deeply appreciated. The active interest and constructive criticism of Dr. E. Rosenblueth are gratefully acknowledged. This paper is the result of intensive discussion between the authors with an attempt to apply such techniques to nuclear structures. The Nuclear Regulatory Commission's Division of Reactor Safety Research supported the work of C. A. Anderson.

References

[1] HART, G. C., and YAO, J. T. P., "System Identification in Structural Dynamics," Invited paper presented at the ASCE Engineering Mechanics Division Specialty Conference on Dynamic Response of Structures, UCLA, California, 30-31 March 1976; Proceedings, pp. 61-85.

[2] RODEMAN, R., Estimation of Structural Dynamic Model Parameters, Ph.D. Thesis, School of Civil Engineering, Purdue University, W. Lafayette, Indiana, August 1974.

[3] RODEMAN, R. and YAO, J. T. P., "Structural Identification - Literature Review," Technical Report No. CE-STR-73-3, School of Civil Engineering, Purdue University, December 1973, p. 36.

[4] MATZEN, V. C., and McNIVEN, H. D., "Investigation of the Inelastic Characteristics of a Single Story Steel Structure Using Systems Identification and Shaking Table Experiments," Report No. EERC 76-20, Earthquake Engineering Research Center, University of California, Berkeley, California, August 1976.

[5] CHEN, S. J. HONG, "Methods of System Identification in Structural Engineering," M.S. Thesis, School of Civil Engineering, Purdue University, West Lafayette, IN 47907, August 1976.

[6] FREUDENTHAL, A. M., "Safety of Structures," Transactions, ASCE, v. 112, 1947, pp. 125-180.

[7] FREUDENTHAL, A.M., GARRELTS, J. M. and SHINOZUKA, M., "The Analysis of Structural Safety," Journal of the Structural Division, ASCE, v. 92, no. ST1, February 1966, pp. 267-325.

[8] "Structural Safety - A Literature Review," Task Committee on Structural Safety of the Administrative Committee on Analysis and Design for the Structural Division, Journal of the Structural Division, ASCE, v. 98, n. ST4, April 1972, pp. 845-884.

[9] FREUDENTHAL, A. M., SHINOZUKA, M., KONISHI, I., and KANAZAWA, T., Editors, Reliability Approach in Structural Engineering, Maruzen Co., Tokyo, 1975.

[10] ANG, A. H-S., and CORNELL, C. A., "Reliability Bases of Structural Safety and Design," Journal of the Structural Division, ASCE, v. 100, n. ST9, September 1974, pp. 1755-1769.

[11] DITLEVSEN, O., and MOHR, G., Editors, Proceedings of Second International Workshop on Definition, Classification, and Evolution of Code Formats, Mexico City, 3-5 January 1976, DIALOG 2-76, Demarks Ingeniorakademi, Denmark, 153 p.

[12] ALLEN, D. E., "Limit States Design - A Probabilistic Study," Canadian Journal of Civil Engineering, v. 2, n. 1, March 1975, pp. 36-49.

[13] GALAMBOS, T. V., and RAVINDRA, M.D., "Tentative Load and Resistance Factor Design Criteria for Steel Buildings," Research Report No. 18, Structural Division, Civil Engineering Department, Washington University, St. Louis, MO, September 1973.

[14] ELLINGWOOD, B. G., "Development of Reliability Based Criteria for Reinforced Concrete Design," Notes for Short Course on Structural Reliability and Design, School of Civil Engineering, Purdue University, West Lafayette, IN, 9-11 March, 1977, 38 p.

[15] LIN, Y. K., "Random Vibration of Periodic and Almost Periodic Structures," Mechanics Today, American Academy of Mechanics, v. 3, 1976, pp. 93-124.

[16] SHINOZUKA, M., "Monte Carlo Solution of Structural Dynamics," International Journal of Computers and Structures, v. 2, 1972, pp. 855-874.

[17] WIRSHING, P. H., and YAO, J. T. P., "A Probabilistic Design Approach Using the Palmgren-Miner Hypothesis," Methods of Structural Analysis, Proceedings of the National Structural Engineering Conference, ASCE, v. II, August 1976, pp. 324-340.

[18] PAEZ, T. L., and YAO, J. T. P., "Probabilistic Analysis of Elastoplastic Structures," Journal of the Engineering Mechanics Division, ASCE, v. 102, No. EM1, February 1976, pp. 105-120.

[19] DER-KIUREGHIAN, A., and ANG, A. H-S., "A Line Source Model for Seismic Risk Analysis," Structural Research Series No. 419, Department of Civil Engineering, University of Illinois, Urbana, IL, October 1975.

[20] WEN, Y. K., and ANG, A. H-S., "Tornado Risk and Wind Effect on Structures," Wind Effects on Buildings and Structures, Edited by K. J. Eaton, Cambridge University Press, London, 1977, pp. 63-74.

[21] ROSENBLUETH, E., "Towards Optimum Design Through Building Codes," Journal of the Structural Division, ASCE, v. 102, No. ST3, March 1976, pp. 591-607.

[22] YANG, J. N., and TRAPP, W. J., "Reliability Analysis of Aircraft Structures Under Random Loading and Periodic Inspection," AIAA Journal, v. 12, No. 12, December 1974, pp. 1623-1630.

[23] LIU, S. C., DOUGHERTY, M. D., and NEGHABAT, F., "Optimal Aseismic Design of Buildings and Equipment," Journal of the Engineering Mechanics Division, ASCE, v. 102, No. EM3, June 1976, pp. 395-414.

[24] GALAMBOS, T. V., and YAO, J. T. P., "Additional Comments on Code Formats," DIALOG 2-76, Denmarks Ingeniorakademic, Denmark, 1976, pp. 24-26.

[25] LIN, Y. K., *Probabilistic Theory of Structural Dynamics*, McGraw-Hill, 1967.

[26] EYKHOFF, P., *System Identification-Parameter and State Estimation*, John Wiley & Sons, 1974.

[27] SHINOZUKA, M., IMAI, H., ENAMI, Y. and TAKEMURA, K., "Identification of Aerodynamic Characteristics of a Suspension Bridge Based on Field Data," IUTAM Symposium on Stochastic Problems in Dynamics, Southhampton, England, July 19-23, 1976, 8 p.

[28] COLE, H. A., "On-Line Failure Detection and Damping Measurement of Aerospace Structures by Random Decrement Signatures," NASA CR-2205, 1973.

[29] COLE, H. A., REED, R. E., "A Method for Detecting Structural Deterioration in Bridges," Report No. NEAR TR71, Nielsen Engineering and Research Inc., Mountain View, CA, July 1974, 91 p.

[30] IBANEZ, P., "Identification of Dynamic Parameters of Linear and Non-Linear Structural Models from Experimental Data," *Journal of Nuclear Engineering and Design*, v. 25, 1973, pp. 30-41.

[31] UDWADIA, F. E., and MARMARELIS, P. Z., "The Identification of Building Structural Systems-I. The Linear Case," *Bulletin of the Seismological Society of America*, v. 66, No. 1, Feb. 1976, pp. 125-151.

[32] MARMARELIS, P. Z. and UDWADIA, F. E., "The Identification of Builiding Structural Systems-II. The Nonlinear Case," *Bulletin of the Seismological Society of America*, v. 66, No. 1, Feb. 1976, pp. 153-171.

[33] POPOV, E. P., and BERTERO, V. V., "Cyclic Loading of Steel Beams and Connections," *Journal of the Structural Division*, ASCE, v. 99, n. ST6, June 1973, pp. 1189-1204.

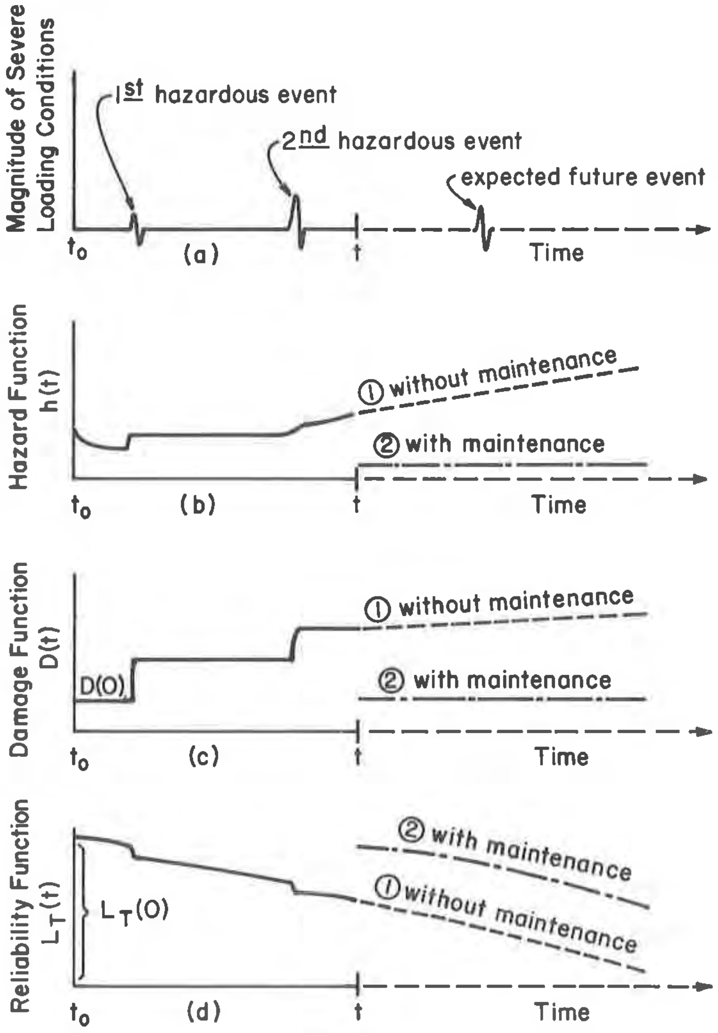
[34] HANSON, R. D., "Comparison of Static and Dynamic Hysteresis Curves," *Journal of the Engineering Mechanics Division*, ASCE, v. 92, n. EM5, October 1966.

[35] "GASSAR 6, General Atomic Standard Safety Analysis Report," General Atomic Company report GA-A13200, v. II, (no date).

[36] SVALBONAS, V., STILWELL, T., and ZUDANS, Z., "Evaluation of the Structural Integrity of High Temperature Gas-Cooled Reactor Core and Support Elements," Franklin Institute Research Laboratories report, F-C4230, (no date).

[37] BENNETT, J. G., JU, F. D., and ANDERSON, C. A., "An Investigation of Failure Mechanisms for HTGR Core Supports," Los Alamos Scientific Laboratory report LA-NUREG-6639-MS (December 1976).

[38] YAO, J. T. P., Summary report presented at the Fourth National Meeting of the Universities Council for Earthquake Engineering Research, University of British Columbia, Vancouver, Canada, June 28-29, 1976.



1. Figure 1 Hazard, Damage, and Reliability Functions