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 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 important 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.,

\[
L_T(t) = P(T > t)
\]

(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:

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

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

\[
L_T(t) = P [ D(t) < 1; 0 \leq t \leq T ] \tag{3}
\]

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:

\[
L_T(t) = L_T(0) \exp \left[ -\int_0^t h_T(t) \, dt \right] \tag{4}
\]

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 \( D_0 \) on some scale less than unity, which may be caused by poor workman-
ship, inferior quality of materials used, or accidental loading conditions during construc-
ton. 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 struc-
ture 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 struc-
ture (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 economi-
cally 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 fatigue 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
stressed. 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

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References


Figure 1  Hazard, Damage, and Reliability Functions