Safety and reliability of existing structures

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Preface

Although many practising engineers have been successfully evaluating tl safety of existing structures throughout the history of structural enginee ing, much of the decision-making process has depended on each engineei experience, intuition, and judgment. In this book, I attempt to examii this problem from several different viewpoints. Several damage functio for civil engineering structures are summarized and reviewed along wi the current practice. Various system identification techniques in structur dynamics are also discussed in terms of their potential applications for tl evaluation of structural safety. To help understand how experts summari and interpret results of measurements, inspection, and analyses in reachii their decision concerning structural safety, the application of rule-infe ence methods is reviewed and discussed. A direct link between su methods and the classical theory of structural reliability is also suggest herein.

As a life-long student of structural safety and an enthusiastic novice the failure behavior of existing structures, I am most interested in learnii all aspects of this challenging problem. I am most fortunate in having mai good friends who are experts in related subject areas both in academ institutions and in private practice. Moreover, I am indebted to n co-workers including B. Bresler, C. B. Brown, S. J. Hong Chen, K. S. F T. V. Galambos, G. C. Hart, J. M. Hanson, M. Ishizuka, S. Toussi f their valuable collaboration. The support of National Science Foundati and encouragement of M. P. Gaus, S. C. Liu, J. Scolzi, and J. E. Goldbe are gratefully acknowledged. The Main Editor of the Monograph Serie W. F. Chen, and Associate Director, John Hindley, of Pitman Publishii Limited provided the necessary impetus and prodding, without which tl work would not have been completed. Marian Sipes capably typed the fi draft of the manuscript.

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Surveys in Structural Engineering and Structural Mechanics

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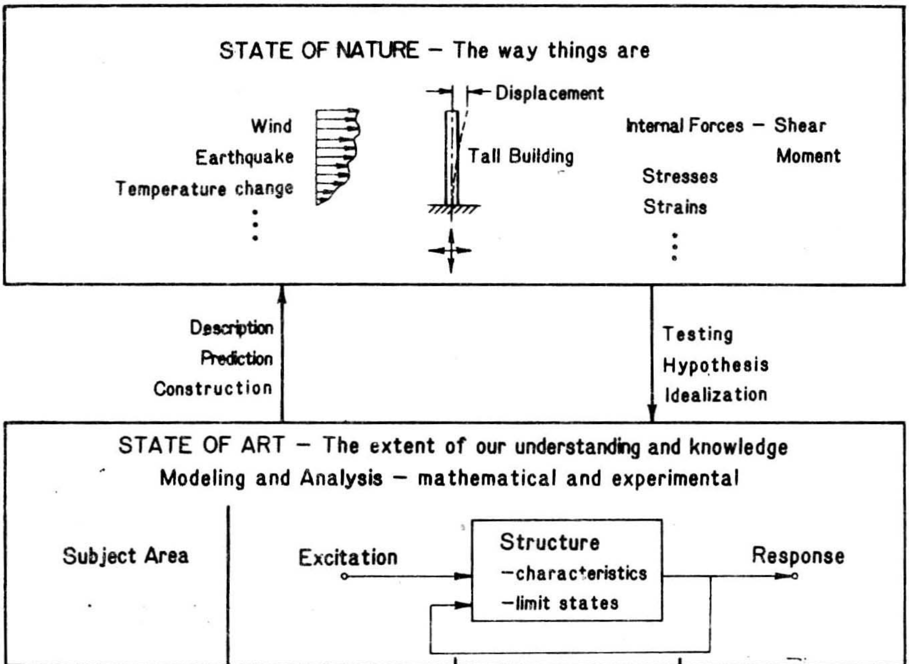
1 Introduction

1.1 General remarks

Various activities in the structural engineering profession have been summarized by Galambos and Yao (62) in terms of the state of nature (the way things are) and the state of art (the body of knowledge). In the state of nature, there exist human and societal needs, environmental conditions, man-made structures, response of these structures to environmental conditions and their consequence and utility. The primary objective of structural engineers is to design these structures to obtain specific structural behavior with desirable consequences and thus satisfy their intended functions to meet certain human and societal needs. On the other hand, the state of the art is an idealization of the complex phenomena in the state of nature for the purpose of making structural analysis and design. Such idealized and mathematical models are in need of continuous updating and improvement.

The interrelationship between the state of nature and the state of art of structural engineering is schematically shown in Fig. 1. In the state of nature, a structure is subjected to excitation (or disturbance or load) such as winds and earthquakes throughout its intended lifetime. The structural response to such excitation can be found in the form of displacements, internal forces, stresses and strains, etc., which present a 'demand' on the structure. Inherently, each structure possesses a 'capacity', which consists of various limit states. Damage or failure may result whenever the demand exceeds the capacity (or one or more components in the response exceed the corresponding limit state(s)).

In general, the structural system and its environment are idealized so that mathematical analyses can be made. The characteristics of a structure can usually be modeled with simple equations. For example, the maximum moment m of a simply-supported beam with length l and a uniformly distributed load w can be found as $wl^2/8$. As another example, the motion of mass–damper–spring systems can be represented with a set of ordinary differential equations. Whenever the load (or disturbance) and the structural model are given or assumed, the process to find the response is called



Subject Area	Excitation	Structure	Response
Structural Analysis	Given (Static)	Given or Assumed	(To be Found)
Structural Dynamics	Given (Dynamic)	Given or Assumed	(To be Found)
Random Vibration	Statistics Available	Given or Assumed	(Statistics to be Found)
Structural Design	Specified	(Configuration to be Found)	Limits Specified
Reliability-Based Design	Statistics Given	(Configuration to be Found)	Limits (Probability) Specified
System Identification	Record (data) Available	(Characteristics to be Estimated)	Record (data) Available
Damage Assessment & Safety Evaluation	Record (data) Available	Results of Inspection Available (Damage or Limit States to be Estimated)	Record (data) Available

Fig. 1 Subject areas in structural engineering

structural analysis. More specifically, when the load is given as a function of time, the subject area becomes known as structural dynamics (100). When the dynamic excitation is random and its certain statistics are available, the methodology for finding essential statistics of the structural response is called random vibration (35). These response statistics can then be used along with resistance (limit states) statistics for the estimation of structural reliability (89).

On the other hand, it is necessary to determine the configuration (including geometry of the structure and size of its members), the material, and the type of construction before the structure is built. In the design process, the loading conditions and limits of the response are specified and the dimensions of the structure are usually sought. As it is well known, the design of a structure frequently follows an iterative process involving both structural analysis and structural design. Because most techniques of structural analysis are applicable only to idealized and simplified systems, the behavior of a completed structure in the state of nature may not correspond to that of the original mathematical model. For certain important structures, nondestructive tests are performed with selected load and response data collected. Techniques of system identification are then applied to obtain a more realistic model for further analysis.

Since the late Professor A. M. Freudenthal presented a rational approach to the structural safety problem more than thirty-five years ago (53), an ever-increasing effort has been directed toward the application of the theory of probability and statistics in structural engineering. In the classical theory (4, 54), the probability of failure or survival for a given type of structure is computed with assumed distributions of random variables representing the load and the corresponding resistance. For structures subjected to dynamic loads, random processes are applied (e.g., (35, 89)). In recent years, several reliability-based design specifications have been developed and adopted around the world (e.g., (2, 5, 34, 104)).

For structures which have been constructed and are thus existing, it is desirable and frequently necessary to assess their respective damage states on the basis of available information including measured and recorded experimental data. In addition, it is desirable to re-evaluate the reliability calculations of these structures so that rational decisions can be made in regard to any necessary repairs, replacements, retirement, and other maintenance or rehabilitation processes.

Whenever it is necessary, a structure can be designed to satisfy code requirements and to perform satisfactorily on the basis of past experience and available knowledge. A site is selected and field data are collected. Usually, a preliminary design is made and the idealized mathematical representation is analyzed for expected or specified loading conditions. Based on these analytical studies, the design may be revised and re-analyzed in an iterative manner until all design criteria are satisfied. The completed design is then implemented through construction as shown schematically in Fig. 2.

Because (*a*) it is difficult to predict future loading conditions and (*b*) materials in the structure possess random characteristics, random

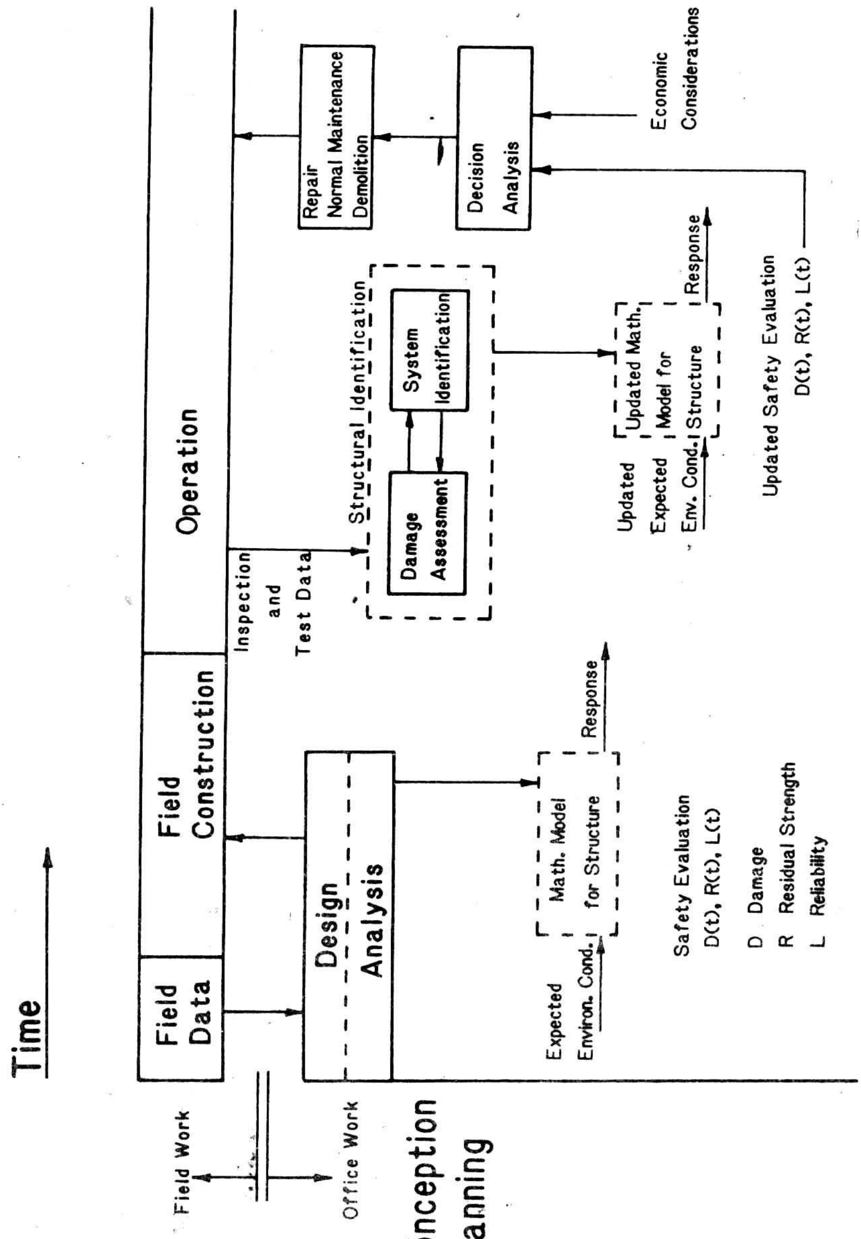


Fig. 2 Role of structural identification

processes have been used to represent these quantities for estimation of failure probabilities. However, the as-built structure is usually different from the original mathematical model in the design process. The fact is that the real-world structure is an extremely complex system. Even with the use of finite element methods and modern computers, it is usually impractical and unfeasible to consider all the details in the mathematical model of a given structure. Moreover, the damage path and failure behavior of most large structures remain unknown because few experimental studies of full-scale structures are available.

For certain important structures, nondestructive dynamic tests are conducted for the estimation of dynamic properties of the as-built structure. These test data are then used to obtain 'improved' or 'more realistic' equations of motion. These equations of motion are applicable within the range of the test amplitude, which is usually small and within the linear behavior of the given structure. Therefore, one cannot apply results of such analysis to include the consideration of destructive or damaging loading conditions. Nevertheless, these mathematical representations can be useful for comparison purposes. For example, any change in the measured natural frequencies may be used as an indicator of structural damage.

Generally speaking, a select group of experienced structural engineers can investigate the condition of a particular structure and determine its level of safety. In such investigations, the original design calculations and drawings (if available) are examined and checked. Inspections and testings are conducted, and the resulting data are analyzed. Results of these analyses are then summarized and interpreted by experienced engineers to yield appropriate recommendations. Although it is possible to understand the inspection and testing conducted and the detailed analysis performed in such studies, the decision-making process involved in deciding (a) specific types of inspection and testing procedures and (b) the summary and interpretation of experimental and analytical results remain the privileged information of relatively few experts in the structural engineering profession.

1.2 Objective and scope

The objective of this book is to summarize and discuss the state of the art of several subject areas related to safety and reliability of existing structures. In Chapter 2, the available damage functions for civil engineering structures are reviewed and discussed. In Chapter 3, current practices for the safety evaluation of existing structures are summarized. In Chapter 4, the role of idstem identification and summarized.pplication to structural dynamics and reliability studies are explored. In Chapter 5, the possible application of rule-inference methods to the assessment of damage is introduced and examined. An attempt is also made in Chapter 6 to propose a unified approach for the solution of problems concerning safety and reliability of existing structures.

2 Damage functions for civil engineering structures

2.1 General remarks

It is desirable to find a generally acceptable and meaningful definition of structural damage for various types of structures. With such a measure of structural damage, the safety of a specific existing structure can be assessed and appropriate decisions regarding repair and maintenance can be made accordingly. In this book, the term 'damage' refers to any deficiency and/or deterioration of strength as caused by external loading and environmental conditions as well as human errors in design and construction. Therefore, a poorly designed and/or poorly constructed structure can have an initial 'damage' measure while it is still new without experiencing any severe loading conditions.

Generally, there are three types of definitions for structural damage. The first one is numerical, the second one is given in terms of repair or replacement costs, and the third one is verbal. Frequently, numerical values are also assigned to various verbal classifications. Some of these definitions are reviewed in Section 2.2. Several problems remain in applying these damage functions in engineering practice. These problems and their possible solutions are presented in Section 2.3. A general discussion of these topics is given in Section 2.4.

2.2 Available damage functions

In 1971, Wiggins and Moran (133) developed a procedure for grading existing buildings in Long Beach, California. A total of up to 180 points is assigned to each structure according to the evaluation of the following five items:

(*a*) *Framing system and/or walls* (0, 20, 40 points) A well-designed reinforced concrete or steel building less than three stories in height is assigned a zero-value. On the other hand, an unreinforced masonry filler and bearing walls with poor quality mortar is assigned a value of 40 points.

(*b*) *Diaphragm and/or bracing system* (0, 10, 20 points) As an example, zero values correspond to well-anchored reinforced slabs and fills. On the other hand, incomplete or inadequate bracing systems correspond to the high 20 points on the scale.

(*c*) *Partitions* (0, 10, 20 points) Those partitions with many wood or metal stud bearings rate zero points. On the other hand, unreinforced masonry partitions with poor mortar will draw 20 points.

(*d*) *Special hazards* (0, 5, 10, 15, 20, 35, 50 points) The high hazards include the presence of non-bearing, unreinforced masonry walls, parapet walls, or appendages.

(*e*) *Physical condition* (0, 10, 15, 20, 35, 50 points) The high hazards include serious bowing or leaning, signs of incipient structural failure, serious deterioration of structural materials, and other serious unrepaired earthquake damage.

For each building thus inspected, all these five numbers are added. The sum may be considered as a damage index. Rehabilitation is not required if the sum is less than 50 points (low hazard). Some strengthening is required if the sum is between 51 and 100 points (intermediate hazard). Demolition or major strengthening is necessary when the sum exceeds 100 points (high hazard).

Detailed guidelines are given for the assignment of numbers in each category. Therefore, this method is relatively simple to use even for inspectors who are not trained as engineers. However, it is difficult to develop such a simple procedure to include all special cases. Moreover, the demarcation between low, intermediate, and high hazards is rather arbitrary for these verbal terms which cannot be clearly defined.

In 1975, Culver *et al.* (36) proposed the field evaluation method (FEM) which is applicable even when building plans are unavailable. A rating of 1 through 4 is assigned for each of the following factors: (*a*) general rating, *GR*, for grading the materials of the frame; (*b*) structural system rating, *s*, for combining ratings of connections, roofs, and floors, etc.; and (*c*) Modified Mercalli Intensity *I*. Then a composite rating, *CR*, is computed as follows:

$$CR = \frac{GR + 2s}{eI} \tag{1}$$

If $CR < 1.0$; the building is said to be in good condition, if $1.0 \leq CR \leq 1.4$; it is in fair condition, if $1.4 \leq CR \leq 2.0$; it is in poor condition, if $CR > 2.0$; it is in very poor condition.

In addition, a more detailed methodology was also presented for survey and evaluation of existing buildings to determine the risk to life safety under natural hazard conditions and estimate the amount of expected damage. There are four major parts in this report as follows:

(*a*) generation of site loads,
(*b*) generation of a structural model,
(*c*) computation of response, drift and ductility, and
(*d*) assessment of damage.

The damage on *i*th story, D_i, resulting from extreme natural environments is expressed in terms of total damage as follows:

$$D_i = F\left(\frac{\Delta_i}{(\Delta_y)_i}\right) \tag{2}$$

where $F(\cdot)$ = distribution function
Δ_i = calculated interstory drift of *i*th story
$(\Delta_y)_i$ = user specified interstory drift corresponding to yielding of *i*th story.

The damage is classified into three categories: structural, nonstructural and glass. It is further subdivided into frame, walls and diaphragms in the case of structural damage.

More generally, the damage can be expressed as sum of the 'initial' damage D_0, and a function of the ductility. Usually, the initial damage is assumed to be zero. Blume and Monroe (13) assumed that the structural damage is linearly related to ductility factor with '0' denoting elastic behavior and '1' denoting collapse. Bertero and Bresler (11) stated that (*a*) the lateral displacement ductility factors generally provide a good indication of structural damage, and (*b*) the interstory drift is a more important factor in causing nonstructural damage. The interstory drift of reinforced concrete buildings during earthquakes was studied extensively by Sozen (1, 99, 120). Bresler (15, 16) discussed the relative merits of using plasticity ratio (residual deformation to yield deformation) and the ductility. For structures which are subjected to cyclic plastic deformations with decreasing resistance, the ratio of the initial to *j*th-cycle resistance at the same cyclic peak deformation was also suggested.

For monotonic loading conditions, Oliveira (102) defined a damage ratio function, D, as follows:

$$D = \left\langle\frac{Z-y}{c-y}\right\rangle^b \tag{3}$$

where Z = maximum displacement response
y = yield displacement
c = displacement at collapse
b = material and structural parameter
$\langle x\rangle^n$ = singularity function such that, for $n \geq 0$, $\langle x\rangle^n = 0$ when $x < 0$, and $\langle x\rangle^n = x^n$ when $x \geq 0$.

For axially-loaded mild steel specimens which are subjected to low-cycle high-amplitude reversed plastic deformations, Yao and Munse (143) suggested the use of the following damage function:

$$D=\sum_{i=1}^{n}\left[\left(\frac{\Delta q}{\Delta q_1}\right)^{1/m}\right]_i \tag{4}$$

where $1/m$ = a parameter depending upon the ratio of the cyclic compressive change in plastic strain to the subsequent tensile change in plastic strain,
Δq = percent cyclic tensile change in plastic true strain,
Δq_1 = percent cyclic tensile change in plastic true strain at $n=1$,
n = number of applications of tensile load prior to fracture.

It is interesting to note that Eq. 3 may be considered as a special case of Eq. 4 with the following correspondence:

$$\Delta q = Z - y$$
$$\Delta q_1 = C - y$$
$$1/m = b$$

Lacking for a well-established cumulative damage law for structural systems, Eq. 4 was applied to evaluate the damageability of seismic structures by Kasiraj and Yao (82, 83) for a given earthquake, and later by Tang and Yao for random ground motions (123, 124). Recently, Rosenblueth and Yao (107) used the following damage function in their study of cumulative damage of seismic structures:

$$D=\sum_{i=1}^{n} a_i\left\langle\frac{Z}{y}-1\right\rangle^{b_i} \tag{5}$$

where a_i and b_i are empirical constants. Although more full-scale and destructive tests are conducted in recent years (7, 61, 72, 95), currently available test data are still insufficient to either validate the form of such a damage function or to estimate these parameters for reinforced concrete structures.

Aristizabal-Ochoa and Sozen (6) used a damage ratio, which is comparable to but not exactly the same as the ductility. The damage ratio is used in the substitute-structures method, with which the inelastic response of the structure can be considered by using a linear dynamic analysis. Okada and Bresler (19, 101) discussed a screening method, in which the reinforced concrete buildings are classified according to three types of failure mechanisms (bending, shear and shear-bending) by considering nonlinear response of the structure to two levels of earthquake motion ($0.3g$ and