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PERFORMANCE OF LOW RISE BUILDINGS - EXISTING AND NEW

James T. P. Yao

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An evaluation of the safety-related seismic performance of existing low-rise building structures is described. The theory of structure reliability is reviewed and error and defect related failures for new constructions are assessed. Failures related to wearout and deterioration also are discussed. Estimation of structural reliability requires determination of the configuration, material, and type of construction. The behavior of an existing completed structure may not correspond to the mathematical model used prior to construction. For certain important structures, nondestructive tests are performed to collect selected load and response data. Techniques of system identification then are applied to obtain a more selective mathematical model for further analysis. An existing structure can be tested either periodically or immediately following an extreme event. Literature relating to new construction failure is reviewed. The need for a set of standard nondestructive testing and inspection techniques is discussed.

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PERFORMANCE OF LOW-RISE BUILDINGS - EXISTING AND NEW

by

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INTRODUCTION

With a few notable exceptions [26], the great majority of structural research projects in earthquake engineering have been concentrated on the analysis and design of high-rise buildings. Therefore, this Workshop presents a unique opportunity for structural engineers to discuss various aspects of the problem concerning low-rise building structures. The word "performance" may mean different things to different people. For example, it can refer to the performance criteria in structural design. It may also imply the response and behavior of existing structures under actual environmental conditions. The seismic performance of existing buildings can be improved by retrofitting, which is certainly different from new constructions. The questions on when and how an existing should be retrofitted remain to be further studied.

Consider the life of any given structure to begin when the construction process is completed at time zero as shown in Figure 1. The well-known "bath-tub" shaped hazard function, $h_T(t)$, is usually divided into three parts. The first part is called the "infantile mortality rate", which reflects error and defect related failures starting with a high value and decreasing with time to a constant at time t_d. The second part is a constant hazard function which implies chance failure. At time t_w, the third part of the hazard function starts to increase due to "wearout" or fatigue types of failures. The dividing time between "new construction" and "existing construction" implies a decreasing or constant hazard function, and the term "existing building" implies a constant or increasing hazard function.

If both the load and the resistance for a given type of structures can be represented with known random processes, it is possible to compute the hazard function for a relatively simple and idealized structure [40-42]. For special cases where sufficient failure data are available, the hazard function can also be estimated statistically. Recently, Drenick and Yun [10] studied the effect of uncertainties in earthquake ground-motion statistics and recommended the combined application of

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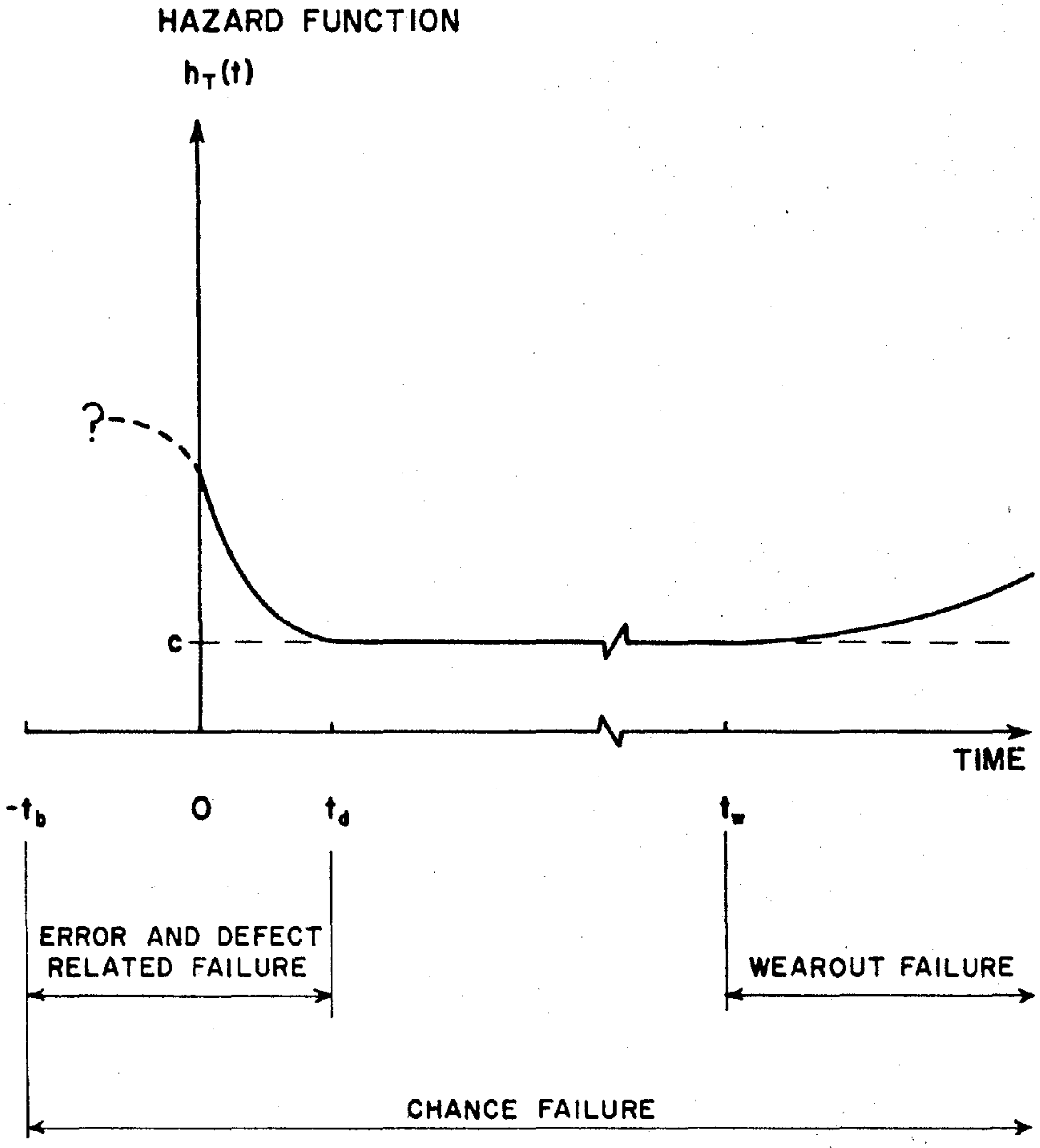


Figure 1. Hazard Function of a Structure

probabilistic methods and worst-case analyses for the realiability study of seismic structures. Nevertheless, difficulties still exist in the safety evaluation and damage assessment of existing structures [43].

Because of my current research interest in structural engineering, the emphasis of this paper is placed on the evaluation of safety related performance of existing structures. An attempt is made to review (a) the theory of structural reliability, (b) error and defect related failures for new constructions, and (c) wearout and deterioration related failures for existing structures. Finally, the need for a set of standard nondestructive testing and inspection techniques is discussed.

THEORY OF STRUCTURAL RELIABILITY

Some 35 years ago, the late Professor A. M. Freudenthal presented a rational approach to the structural safety problem and thus formally established the subject area of structural reliability [13]. The extensive state-of-the-art of this important topic was summarized in a 1972 report of the American Society of Civil Engineers/Structural Division/Task Committee on Structural Safety [36]. In 1974, a reliability-based design code format was presented to the civil engineering profession [37]. To-date, the theory of structural reliability has been applied to solve various practical problems in earthquake engineering, wind engineering, ocean engineering, aerospace structures, and nuclear structures [14].

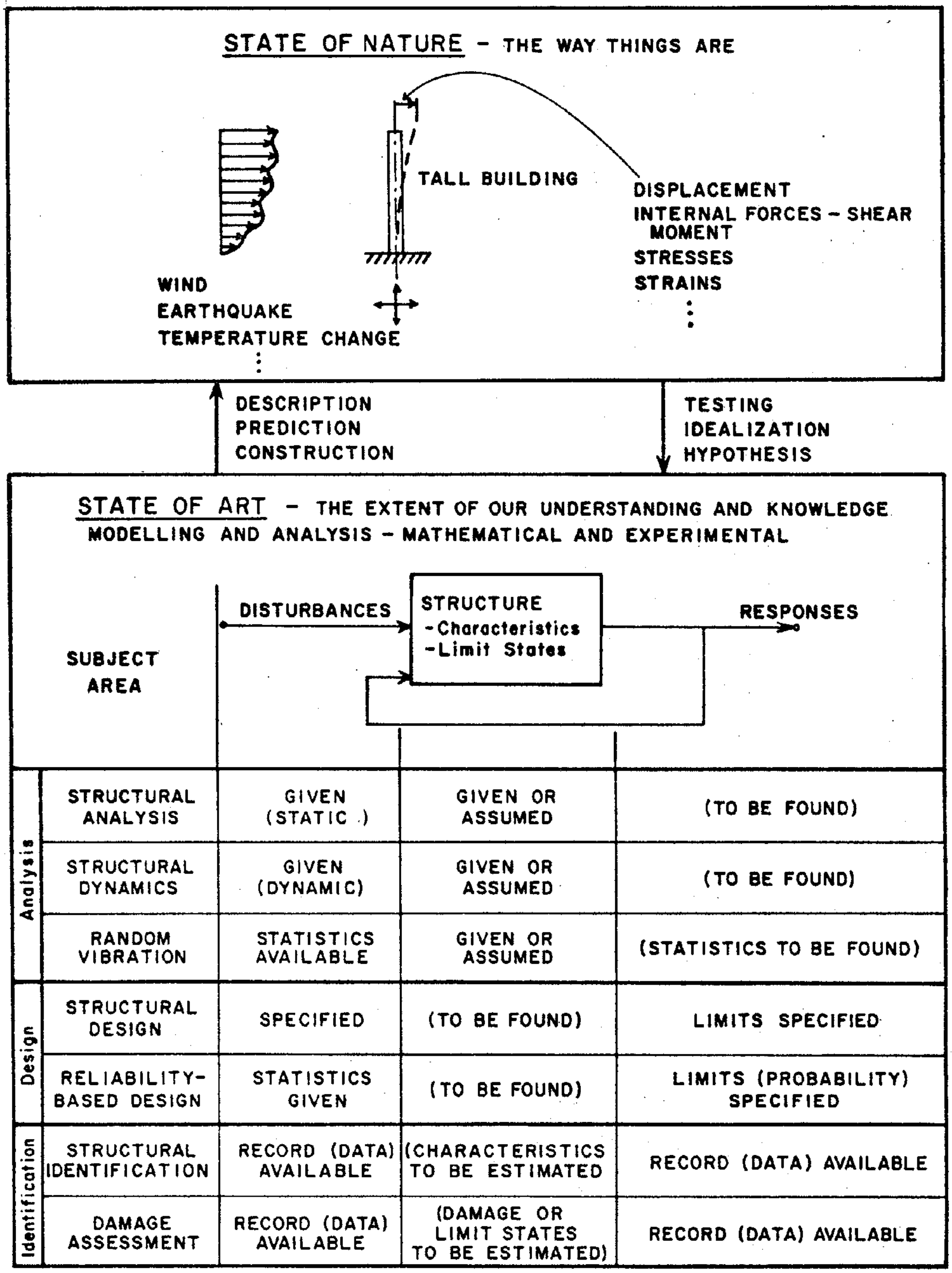
The interrelationship between the state of nature (the way things are) and the state-of-the-art (the extent of our understanding and knowledge) is illustrated in Figure 2. In the state of nature, a structure is subjected to disturbances throughout its intended lifetime. The responses of the structure to such disturbances exist in various forms such as displacements, internal forces, stresses and strains, which present a "demand" on the structure. Inherently, each structure possesses a "capacity", which consists of various limit states corresponding to respective demands. Damage or failure may result whenever one or more demands exceed corresponding capacities. The reliability function, $L_T(t)$, for a given structure is defined as the probability that the structure will survive at least time t, i.e.,

$$L_T(t) \equiv P(T > t) \tag{1}$$

Where $P(T > t)$ denotes probability, and T is a random variable denoting the useful lifetime of the structure. Alternatively,

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

where $R(\tau)$ and $S(\tau)$ denote the resistances (capacity) and response to disturbances (demand) of the structure, respectively. The reliability function is related to the hazard function in the following manner:



	SUBJECT AREA	DISTURBANCES	STRUCTURE -Characteristics -Limit States	RESPONSES
Analysis	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)
Design	STRUCTURAL DESIGN	SPECIFIED	(TO BE FOUND)	LIMITS SPECIFIED
	RELIABILITY-BASED DESIGN	STATISTICS GIVEN	(TO BE FOUND)	LIMITS (PROBABILITY) SPECIFIED
Identification	STRUCTURAL IDENTIFICATION	RECORD (DATA) AVAILABLE	(CHARACTERISTICS TO BE ESTIMATED	RECORD (DATA) AVAILABLE
	DAMAGE ASSESSMENT	RECORD (DATA) AVAILABLE	(DAMAGE OR LIMIT STATES TO BE ESTIMATED)	RECORD (DATA) AVAILABLE

Figure 2. Subject Areas in Structural Engineering - A Classification.

$$L_T(t) = L_T(t_0) \exp [-\int_{to}^{t} h_T(t)dt] \quad (3)$$

where $L_T(t_0)$ is the initial value of the relaibility function at time t_0. Generally, the structural system and its environment are represented with mathematical idealizations for the purpose of analyses. Whenever the mathematical representations for disturbance and the structure are given or assumed, the process to find the desired responses is called structural analysis. More specifically, when the load is given as a function of time, the subject area is known as structural dynamics. When the dynamic excitation is random with certain statistics available, the methodology for finding certain statistics of the structural response is called random vibration (e.g., see [8,21]). These response statistics can then be used along with resistance (limit states) statistics for the estimation of structural reliability.

Meanwhile, it is necessary to determine the configuration (including geometry of the structure and sizes of its members), the material, and the type of construction before the structure is constructed. In this design process, the loading conditions and limits of the response are specified and the dimensions of the structure usually follows an iterative process involving both structural analysis and structural design. Some recent developments on design code formats are summarized in 1976 [9]. A practical example of the current generation of reliability-based design code in the load and resistance factor design (LRFD) as described by Galambos et al [16]. Optimum design processes were also discussed [23, 32].

Because most techniques of structural analysis are applicable only to idealized systems, the behavior of a completed sturucture in the state of nature may not correspond to that of the mathematical model as used prior to the construction. For certain important structures, nondestructive tests are performed to collect selected load and response data. Techniques of system identification (e.g., [11]) are then applied to obtain a more realistic mathematical model for further analysis. Such studies are a part of the subject area of structural identification [7, 17, 31]. It has been suggested to extend such applications for the estimation of damage and reliability of existing structures following the occurrence of severe earthquakes [24, 43]. Recently, attempts are also being made to obtain a rational formulation for the safety evaluation and damage assessment of existing structures [45].

An existing structure can be tested and inspected either periodically or immediately following an extreme event. Ideally, these test data and inspection results can be used for the following two purposes: (a) to assess the damage (or safety) state of the structure at the time of test and inspection, and (b) to modify the mathematical representation of the structural system for further safety and reliability analysis. As an example, when a new structure is first completed, the reliability of the structures in the next fifty years (design life) is given by Equation 3 as follows:

$$L_T(50) = L_T(0) \exp [-\int_{0}^{50} h_T(t)dt] \quad (4)$$

where $L_T(0)$ may be assumed as unity, and $h_T(t)$ may be based on some idealized mathematical analyses prior to any testing or inspection of the completed structure. When the structure is six years old, there is a strong earthquake which causes some damage to the structure. Then, the structural reliability using test data and inspection results can be revised as follows:

$$L_T^{(1)}(50) = L_T^{(1)}(6) \exp [-\int_6^{50} h_T^{(1)}(t)dt] \qquad (5)$$

where $L_T^{(1)}(6)$ represents the present damage (or safety) state of the structure, and $h_T^{(1)}(t)$ reflects the modified mathematical representation of the structure system following one major earthquake. The comparison of $L_T(50)$ and $L_T^{(1)}(50)$ may help the engineer to decide whether and how the structure should be repaired. More generally, the updated reliability function after ith inspection can be given by:

$$L_T^{(i)}(t) = L_T^{(i)}(t_i) \exp [- \int_{t_i}^{t} h_T^{(i)}(t)dt] \qquad (6)$$

In reality, however, it is still difficult to estimate $L_T^{(1)}(t)$, and $h_T^{(1)}(t)$ on the basis of test data and inspection results.

NEW CONSTRUCTION

Because most failures for new constructions can be related to human errors and defective components, available literature in this regard is reviewed herin. Recently, Fraczek [12] reported on the results of a study of some 277 cases of errors concerning reinforced concrete structures. Because many practicing engineers are reluctant to disclose error-related failures, these results were extracted from incomplete responses to a survey which was conducted by the ACI Committee on Structural Safety. Nevertheless, results of this study indicate that (a) design errors are more prevalent than construction errors in connections, joints, and prestressed concrete members, (b) most design errors are detected during occupancy and cause serviceability malfunctions, and (c) nearly three-fourth of construction errors are detected and over one-half of these errors cause distress or failure. In conclusion, Fraczek recommended to conduct a new survey for the collection of further information because of the following difficulties that he and the ACI Committee encountered: (a) some responses were vague and ambiguous, (b) the terms "failure" and "distress" were interpreted in a subjective manner by various respondants, (c) the present survey was found to be biased toward errors which were detected following the completion of the constuction process, and (d) the sampling process may not be statistically valid partly because many engineers chose not to reply to the Committee during the present survey.

Allen [18] summarized the results of a seminar on the relation between human error and civil engineering structures, which was held in Ontario, Canada on 15-16 October 1979. Participants of this seminar include; W.R. Schriever, F. Knoll, A. Nowak, R.F. Scott, N.C. Lind, E. Y. Uzumeri, R. G. Sexsmith, Z. S. Shah, C. J. Turkstra, H. Mathieu, and N. FitzSimons. As a group, they discussed the subject in detail and made recommendations with regard to research, organization, codes and standards, collection of failure information, and information feedback. Some 19 references were listed.

Because most failures were found to be related to human error or unexpectedly extreme loading conditions [1, 35], Nowak [27] attempted to estimate the effect of gross errors on structural safety by considering one possible error at a time. There exist several means of controlling gross errors, which include (a) inspection; (b) proof loading, and (c) adjustment of design safety factors. Nowak suggested that the choice of the type and the degree of error control can result from an economic analysis. Recently, a series of papers on these topics have been presented [3, 22, 25, 28, 30, 38].

Eventually, it is hoped that any detected defects and/or expected errors in a given new construction can be used to modify both $L_T(t_O)$ as well as $h_T(t)$ in Equation 3. Thus, the reliability estimate $L_T(t)$ can be improved with the use of test data and inspection results.

EXISTING BUILDINGS

It is desirable to assess the safety state of existing structures either periodically or immediately following each major catastrophic event such as a strong earthquake. On the basis of such assessments, decisions can be made on whether a particular structure should and can be repaired. One recent example of extremely sever earthquakes is the 28 July 1976 Tangshan earthquake in the Hopeh Province in China. Jennings [19] reported that over 75 percent of the 916 larger brick buildings (most are two to four stories in height) collapsed or were severly damaged. It is also interesting to note that studies of the response characteristics of building structures showed considerable differences in the fundamental periods in comparison with undamaged structures.

In case of need, the condition of any existing building structure can be evaluated either experimentally or analytically. Analytical studies include (a) the examination of available design calculations and drawings, (b) the review of applicable specifications, and (c) the anlaysis of the structure with the use of additional field observations. Experimental investigations frequently consist of (d) the determination of locations of failures, (e) the application of non-destructive testing, (f) the detection of defective components and (g) the proof-loading of the structure. Although such evalution are known to exist in general, the detailed methodology including the decision-making process remains as privileged information for a relatively few experts in the profession [43].

It is desirable for structural engineers to assess the degree of deterioration in resistance and to evaluate the reliability of a particular structure at any given time [24, 39]. When a structure is inspected for the purpose of making damage assessment, a series of nondestructive tests may be performed and the resulting data can be analyzed accordingly. Measurable quantities during these tests include loads, deformation or strains, and accelerations. From these experimental data, (a) mechanical properties such as stiffness and strength, and (b) dynamic characteristics such as natural frequency and damping can be estimated. Moreover, visible damage features such as cracks and permanent deformations can be detected by experienced inspectors.

One possible approach to the structural identification problem is to obtain a damage function, the parameters of which can then be estimated using testing and inspection data. Blume and Monroe [4] assumed that the damage is linearly related to the ductility factor with "0" denoting elastic behavior and "1" denoting collapse. Bertero and Bresler [2] stated that (a) the lateral displacement ductility facotrs generally provide a good indication of structural damage, and (b) the inter-story drift is a more important factor in causing nonstructural damage. Bresler [5] discussed the relative merits of using plasticity ratio (residual deformation to yeild deformation) and the ductility. For structures which are subjected to cyclic plastic defromations with decreasing resistance, the ratio of the initial to jth-cycle resistance at the same cyclic peak deformation was also suggested.

For monotonic loading conditions, Oliveria [29] defined a damage ratio function, which is analogous to a special case of a damage function as developed for axially-loaded mild steel speciman subjected to low-cycle and high-amplitude reversed plastic deformations [48]. This earlier damage function as given by Yao and Munse [48] was used to evaluate the safety of structures by Kasiraj and Yao [20] for a specific earthquake excitation, and later by Tang and Yao [34] for random ground motions. In an unpublished technical note, Rosenblueth and Yao [33] introduced a damage function in their pilot study of cumulative damage of seismic structures. Unfortunately, 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.

Ultimately, it is desirable to obtain (a) some measure of the current safety (or damage) state such as $L_T^{(i)}(t_i)$, and (b) the modified hazard function $h_T^{(i)}(t)$ with the use of test data and inspection results which are obtained at time t_i. In this manner, the reliability of the structure at some future time $t(>t_1)$ can be estimated (such as $L_T^{(1)}(50)$) in equation 5).

RESEARCH NEEDS AND CONCLUDING REMARKS

Refer to Figure 1, the hazard function during the time period between the beginning of construction, $-t_b$, and the completion of construction, 0, seems to require further study. Quantitatively, the building gegins with bare ground at time $-t_b$ and ends with a full structure at time zero. Therefore, the fact that the structure itself changes with time (time-variant) makes the analytical problem of computing or estimating the hazard function more interesting and challenging. Moreover, it is desirable to collect relavant data for the statistical inference of this hazard function.

According to Zadeh [49, 50], as the complexity of a system increases, our ability of making precise and yet significant statements concerning its behavior diminishes. Consequently, the closer one looks at a real-world problem, which is usually complex, the fuzzier its solution becomes. All existing buildings are indeed complex systems, the complete behavior (including various degrees of damage) of which cannot be easily and clearly described. The application of fuzzy sets to several civil engineering problems was reviewed recently [6, 44]. Moreover, an attempt was made to apply the theory of fuzzy sets to the complex problem of damage assessment of existing structures [46].

Finally, it is desirable to develop a standard set of nondestructive inspection and testing procedures for all existing structures, whether they are new or old. Depending on the value and failure consequences of each building, a certain procedure can be selected and followed. To properly interpret these inspection and testing data, a rational methodology needs to be formulated. Recently, Fu and Yao [15, 41] proposed to use the theory of pattern recognition in such studies. Other topics for further research are also listed [47]. Much of this research for low-rise buildings will be common for existing and new buildings alike.

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