On Structural Reliability

James T. P. Yao

Texas A&M University, College Station, TX 77843-3136, U.S.A.

Hiroshi Kawamura

Department of Architecture and Civil Engineering, Kobe University, Rokkodai, Nada, Kobe, 657-8501, Japan.

(Received 24 January2001; accepted 21 September 2001)

In this paper, we summarize our viewpoints on structural reliability including the effects of structural control and symptom-based reliability for readers who may not be structural engineers. Structural reliability, which refers to the application of probabilistic methods in studying structural safety, depends very much on temporal factors. Traditionally, structural reliability has been defined as the probability of the useful life of a given structure exceeding a certain time-period, t. It is a good measure of the level of safety for structures that are made of various materials. However, the authors are convinced that it is more meaningful to base reliability of existing structures on symptoms that can be related to structural damage. We will describe the symptom-based reliability in more details later. Control systems can be considered as additional redundancies that improve the structural reliability. Recently, many active control systems (both passive and active) have been developed and used in bridges and buildings, especially in Japan. Fuzzy control has also been studied. In the seventies, efforts were made to apply structural reliability in design codes resulting in LRFD (Load and Resistance Factor Design) specifications. Nevertheless, almost every expert is an analyst. We believe that no further progress can be made unless many more experiments will be conducted. Structural reliability will be applied to performance-based design, and structural performance should be assessed for structural sustainability and adaptability to the temporal changes of natural and social environments. Our viewpoints along these lines have been expressed herein.

Keywords: existing structures, structural control, structural reliability, symptoms, fuzzy theory

1. INTRODUCTION

Freudenthal [1] was among the first in the world to develop structural reliability that is the application of probabilistic methods to evaluate the safety of structures that are made of various materials. For example, a steel structure that was designed with a factor of safety of 1.7 cannot be compared directly in safety with a concrete structure that was designed with a load factor of 2.4. However, these two structures can be compared with their respective probabilities of failure whenever they can be evaluated. His work on the classical theory of structural reliability was summarized in a comprehensive manner by Freudenthal et al. [2]. Since then, because (a) there is insufficient amount of experimental data to ascertain the tail ends of probability distributions (that are significant in calculating the failure probability) and (b) it is easier to formulate design formulae on the basis of the first two moments, attention was given to develop probability-based design codes such as the LRFD (Load and Resistance Factors Design).

Pau [3] discussed diagnosis and monitoring in terms of various modes of failure. He also illustrated the relationships of performance, monitoring, and diagnosis of mechanical systems. Cempel [4] showed that the use of symptom-based reliability was more meaningful than the age-based reliability for existing mechanical systems. At one time many years ago, Dr. C. Cempel, a mechanical engineering professor in Poland, tested 3,000 diesel engines, all were 10-year old. Some of these engines were used almost continuously while others were used sparingly during these ten years. The symptom measured by Professor Cempel was the noise level after an engine was started. The noisier the engine, the shorter remaining life it had. The same principle may be applied to civil engineering structures. For example, consider a number of identical highway bridges. Some of these bridges had high volume of heavy traffics and are subjected to corrosive environments while others with light traffic and no possibility of corrosion. As another example, some buildings are subjected to heavy internal and external loads while others to light loads. However, it is not clear as to what symptoms are indicative of structural damage in these structures. Attempts have been made to apply the symptom-based reliability to civil infrastructure systems (e.g., see Cempel et al. [5], [6]; Natke and Cempel [7]; Wong and Yao [8]; Yao et al. [9], [10]). At present, it is necessary to find significant symptoms indicating structural damage of existing structures in civil engineering.

Professor Zadeh [11] published the first paper on the theory of fuzzy sets. Basically, the theory of fuzzy sets deals with those events that are meaningful but not well defined. For example, the damage of a structure might be classified as collapsed, severely damaged, lightly damaged, and not damaged. With the exception of the category of "collapsed," the other classifications are meaningful but not clearly defined and thus they are fuzzy events. Therefore, the theory of fuzzy sets can be used in such cases. Although civil engineers were among the first to apply the theory of fuzzy sets (Wong et al. [12]), there have been very few practical applications to date. In structural reliability studies, there are many vague terms that fuzzy sets are potentially applicable. In order to deal with engineering assessments generally and systematically, a concept of fuzzy network and its application were proposed (Kawamura and Yao [13]; Kawamura [14]; and Kawamura et al. [15]).

2. LRFD SPECIFICATIONS

Since the seventies, various forms of Load and Resistance Factor Design (LRFD) incorporating the reliability concepts have been developed and implemented around the world. Basically, a safety or reliability index as a function of the first two moments of a performance function in terms of loads and resistances is used (in lieu of the traditional factor of safety or margin of safety) in these specifications. Although experimental results have been used in the development of these design codes, the experts of structural reliability today consisted of almost exclusively analysts. The adoption of these design codes in various countries represented a major break-through in structural reliability. However, these design codes were written in such a way that no explicit mention to probability (or reliability) for fear of scaring off practicing engineers. Today, there has been a trend to compute the exact probability of failure again (e.g., Schueller et al. [16]; and T. Yao and Wen [17]). The fact remains that there has not been sufficient data to determine the tail ends of probability distributions to date. We believe that, until such a time when abundant experimental data are available to ascertain the tail portions of probability distributions, it is essentially useless to compute the exact probability of failure. Instead, the notional failure probability can be used to show the relative advantages of different designs indicating the levels of safety. In addition to the incompleteness of the past data, another assumption of probability theory that the same phenomena will be repeated in the future is not realistic, because every thing is changing with time. Strictly speaking, structural reliability should be always renewed according to unexpected changes of structural conditions and environments. Therefore, in the application of LRFD, temporal and actual factors should be considered.

3. STRUCTURAL CONTROL

The concept of structural control is simple and straightforward. Whenever the structural response (e.g., deflection, stress, or strain at certain points of a structure) is exceeding limiting values, forces are generated to reduce them. Soong [18] summarized basic principles and practical applications of structural control. Passive control devices would result in much smaller demand. As an example, use the deformation in the performance function. Assuming a constant deformation capacity, a smaller deformation demand results in a small failure probability. Meanwhile, the structural reliability of an actively controlled structure can be more complicated. Such a reliability can be a function of power supply, components of the control device, etc. On the other hand, the presence of active control may be considered as an additional redundancy that reduces the failure probability. If we design a structure using the active control system only under extreme conditions, most structures will go through their useful lives without the necessity of activating control devices. In such cases, even if the reliability of the control device is low, it is advantageous to have the active control system in the structure. In the following, we use a simple example to demonstrate this concept.

Consider a structure without active control systems. The failure probability is given by

$$P_f = P\left[g(\underline{X}) \leq 0\right] \tag{1}$$

where g(.) denotes the performance function. For structures with active control, let MACD represent the event of malfunction of active control devices. For structures with redundant control systems,

$$P_{\text{fac}} = P\left[g(\underline{X}) \leq 0/\text{MACD}\right] * P(\text{MACD}) \tag{2}$$

Therefore,

$$P_{fac} \leq P_f \tag{3}$$

Because the structural reliability is defined as the complement of failure probability, in terms of reliability functions,

$$L_T \leq L_{Tac} \tag{4}$$

However, it can not necessarily be said that L_T is always smaller than L_{Tac}, because the real effects of time delay and spillover are often unpredictable in the case of active control. Furthermore, it is very difficult to assess P(MACD).

Structural control can be considered as additional redundancies that would improve the reliability. Generally in case of the structural design against earthquake loadings, it is very difficult to estimate the failure probability of structures strictly because of the irregularity and time-dependence of earthquake occurrences and loadings (Kawamura, Yamada, Tani and Teramoto [19]; Kawamura, Tani and Yamada [20]). Especially in case of the active structural control against earthquake loadings, reliability functions should be based on other factors than the failure probability of structures with active control devices. The reason is that in active control systems optimal control forces have to be acted successively during earthquakes simultaneously with successive prediction of earthquake motions and identification of structures. Considering various uncertainties of earthquake loadings, structures and control devices, the theory of fuzzy sets is more practical for assessing future events than probability theory. Probability density functions and/or cumulative functions can be replaced by fuzzy membership functions. If one of the purposes of the reliability theory is to be utilized for engineering decision-making and for performance-based design, and if reliability- and performance-based structural control is aimed at, fuzzy maximizing decision will satisfy these conditions. In structural active control systems, it is shown by digital simulations that an optimal control one with fuzzy maximizing decision is very effective and practical (Kawamura and Yao [13], [21]; Kawamura and Tani et al. [22]; Tani and Kawamura [23]; Tani and Kawamura et al. [24]; and Fujitani et al. [25]), because both the fracture behaviors of structures and control devices can be taken into account simultaneously in the proposed system which can be called performance-based control.

4. SYMPTOM-BASED RELIABILITY

Most existing structures are complex. Many experienced structural engineers can assess the condition of structures and detect structural damage on the basis of visual inspections and simple nondestructive tests. Therefore, attempts have been made to establish expert systems (e.g., see Furuta et al. [26]).

Yao [27] discussed reliability issues in general. He believed that symptom-based reliability as presented by Cempel [4] could be useful in damage detection of existing structures. Nevertheless, unlike the mechanical systems that Cempel et al. (e.g., [5], [6]) applied, the significant symptoms of civil structures are still unknown at present. Various investigators (e.g., Yao and Wong [10]; Yao and Yao [9]) have been looking for these symptoms for practical application. Meanwhile, Wong et al. [8] emphasized the need to convince stakeholders of the necessity of using symptom-based reliability in structural health monitoring.

5. DISCUSSION AND SUMMARY COMMENTS

Progress has been made in many fronts of structural reliability. For examples, system reliability (e.g., see Frangopol [28]), bridge engineering (e.g., see Frangopol et al. [29]), and optimization studies (e.g., see Frangopol et al. [30]) have all gained a lot of ground during this period. In our minds, however, there has not been another major breakthrough since LRFD specifications were implemented around the world.

1. Roesset and Yao [31], [32] suggested several topics for further research. However, no concrete steps have been taken in these directions to date. Several attempts (in lieu of probability theory) have been made by Kawamura et al. as follows: a fuzzy performance-based design method (Kawamura et al. [33]), a fuzzy structural planning method with LCA (Life Cycle Assessment) (Iwata and Kawamura et al. [34]), an evolutionary active control system (Mitsui et al. [35]; and Tani et al. [36]), and an evolutionary intelligent building structural planning system (Kawamura et al. [37]). In order to maintain structural sustainability and adaptability to the future temporal changes of natural and social environments, one of design objects is considered to be recurrent structures with recycle-, reuse-, and repair-types. Based on historical and present observations and subjective fuzzy assessments of future events, structural reliability would become more adaptable to such a structural recurrence. Structural control systems should also be designed in that sense.
2. We believe that the symptom-based reliability can be more meaningful than the time-based reliability for existing structures. It behooves us to find symptoms that can be related to structural damage and measure these symptoms in order to predict the remaining life for each structure.
3. The theory of fuzzy sets can be used in cases where the terms are meaningful but not clearly defined. As examples, a structure can be described as fuzzy events as “severely damaged” or “moderately damaged.” Fuzzy optimal

control can also be used as Kawamura et al. [21], [22] showed.

ACKNOWLEDGEMENTS

We wish to thank Professor Yoichi Ando for his kind invitation, without which this paper would not have been materialized. In addition, we acknowledge the supports of the Grant-in-Aid for Scientific Research of the Ministry of Education, Science and Sports and Culture in Japan and the Lohman Professorship in Engineering Education at Texas A&M University in USA.

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