Damage Evaluation for Structural Reliability Assessment

J.T.P. Yao

Department of Civil Engineering, Purdue University, West Lafayette, Indiana 47906, U.S.A.

Summary

The objective of this paper is to present the state-of-the-art on damage evaluation and its relationship with reliability estimations for existing structures. Possible extension of available results and potential research problems in the application to nuclear structures are also discussed.

Following the construction of an important structure, it is desirable for structural engineers to make periodic inspections. Results of such inspections should be interpreted in terms of structural safety upon which a decision can be made as to whether and how the structure should be repaired. A number of publications on this subject matter have been reviewed and discussed herein. Because the failure behavior of any existing structure is too complex to be modelled mathematically in a precise manner, it is necessary to use expert opinion in the decision-making process. It is also desirable at present to develop interactive rule-based systems. These methods can be extended and applied to solve relevant problems related to nuclear structures. Meanwhile, studies are being made concerning dynamic testing of as-built nuclear power plates. Results of such tests and/or recorded structural response data during wind storms or earthquakes can be useful inputs for a damage assessment system such as the SPERIL-I described herein. It is concluded that further research is required for such practical applications.

1. Introduction

In the classical theory [1-3], the reliability function, $L_T(t)$, for a given structure, is defined as follows:

$$L_T(t) \equiv P(T > t) \quad (1)$$

where T is a random variable denoting the useful lifetime of the structures. The reliability function can also be expressed in terms of the hazard function, $h_T^{(i)}(t)$, as follows:

$$L_T(t) = L_T(t_i) \exp\left[-\int_{t_i}^t h_T^{(i)}(\tau) d\tau\right] \quad (2)$$

where t_i denotes the time for i th inspection; $L_T(t_i)$ denotes a up-dated measure of the safety level at t_i ; and $h_T^{(i)}(\tau)$ denotes a revised hazard function as a result of the i th inspection. Eq. (3) is used to illustrate that there are two aspects of the reliability problem for existing structures. One is concerned with the estimation of the safety (or damage) level at the time of inspection, and the other is the modified function representing future hazard or risk [4,5].

To improve these mathematical representations for a particularly important structure such as a nuclear structure, the completed structure can be tested with known forcing functions. The recorded response data can then be analyzed using techniques of system identification [6]. Meanwhile, a given structure can be studied either (a) when there are signs of distress or failure, or (b) as following a periodic inspection procedure [7]. Although general procedures for such investigations are known, the decision making process remains as privileged information for a relatively few experts. Recently, Ishizuka et al. [9] presented a computer-based system for the assessment of structural damage. Other approaches are also available [9-11]. Possible applications of such techniques for the assessment of earthquake damage to pressure vessels were discussed [12], and the interpretation of dynamic response measurements for the assessment of structural damage were studied recently [13,14].

The objective of this paper is to present the state-of-the-art on the subject matter of damage evaluation and its relationship with reliability estimations for existing structures. Possible extension of available results and potential research problems in the application to nuclear structures are also discussed.

2. Mathematical Modelling

In making structural analysis prior to the construction phase, it is necessary to use general mathematical models available to-date with calculated or assumed parameters. Frequently, structural engineers are asked to test and inspect a structure only after the occurrence of a hazardous event such as a strong-motion earthquake and/or the observation of structural damage. Results of these tests and inspection are then used as the bases for engineers' recommendations as to whether and how the structure should be repaired. To-date, such evaluations and assessments depend a great deal on the experience and intuition of relatively few structural engineers.

When a structure is tested for system identification purposes, the amplitudes of various responses must be kept low to avoid the possibility of damaging the structure. While the resulting mathematical representations from using such test data are adequate in structural analysis for serviceability considerations, the usefulness of such mathematical models in the case of severe loading conditions such as strong earthquakes is questionable. Moreover, it is known that structural behavior under extreme loading conditions can be highly nonlinear and inelastic and therefore highly loading-history dependent. Under these circumstances, the extension of such models with other severe loading conditions may not be justified. A recent example of such difficulties can be found in a progress report on a recent full-scale experimental study [15].

3. Damage Functions

A normalized scale ranging from zero to unity can be used to denote the structural damage with zero indicating "no damage" and unit indicating "total damage". As an example, in the case where the loading is monotonic, Oliveira [16] defined a damage ratio function, in terms of the maximum plastic deformation. For structures which are subjected to low-cycle high-amplitude reversed plastic deformations, Yao and Munse [17] suggested the use of the following damage function:

$$D = \sum_{i=1}^n \left[\frac{Z_i - Y_i}{C_i - Y_i} \right]^{\alpha_i} \quad (3)$$

Eq. (3) was applied to evaluate the damageability of seismic structures for deterministic loads [18] and for random loads [19].

In 1971, Wiggins and Moran [20] proposed an empirical procedure for grading existing building structures in Long Beach, California. Later,

Culver et al [21] proposed the field evaluation method (FEM). Bresler, Okada, and Zisling [22] commented later that the composite rating formula is rather arbitrary. In 1977, Bertero and Bresler [23] suggested a normalized cumulative damageability index which is the sum of local damage indices. Although attempts have been made to compute such indices for actual cases [24], further investigations are needed to make this method more practical and useful.

Recently, results of several other investigations have been reported [25-27]. Kustu et al. [27] collected laboratory test data in the form of force-deformation relationships. They defined a set of damage states for each type of component. Either a normal or a lognormal distribution was used to represent the statistical variations of various damage threshold values. A "central damage factor" is defined as the ratio of the estimated cost of repairs for a damage state to the replacement value of the component in question. The conditional probability of a component being in a damage state given a calculated demand is then calculated. Finally, the expected damage can be calculated. Such a procedure is logical and the report was well written. Nevertheless, the following questions may be raised. First, there are too many types of components and too many different designs to obtain sufficient data for detailed statistical analysis in all possible cases. Second, the demarcations between adjacent damage states are not clearly defined. Third, there are questions concerning the calculation of the demand in the structural component (e.g., see [15]). Finally, it seems that is difficult to evaluate the central damage factor in reality.

4. Damage Assessment Studies

Several recent damage assessment studies are reviewed in a comprehensive manner by Scholl et al. [28]. They recommended a similar procedure to that of Bertero and Bresler [23] in which the damage to a structure is defined as the sum of the component damage which in turn are sums of sub-component damage.

Existing structures in the real world are extremely complex systems (e.g., see [15]). In many cases, a complex real-world problem can be divided into a sequence of simpler questions, which can best be answered by experienced engineers with descriptive words or phrases. The theory of fuzzy sets [29] is a potentially useful tool with which such answers can be interpreted for the solution of the original problem. In an introductory paper, Brown and Yao [30] classified engineering problems into four different types depending upon whether the uncertainties in prior information and updating are statistical or imprecise. They concluded that problems involving uncer-

tainties of the imprecise type require the development of new theories and techniques in their solution [30].

The fuzzy set theory has been applied to civil engineering problems of decision-making in recent years [30,31]. To assist structural engineers in making important decisions concerning whether and how a given structure should be repaired, a rule-based damage assessment system called SPERIL-I has been developed [8]. Although the current version of SPERIL is not yet sufficient for practical applications, it serves the purpose of demonstrating the feasibility of a systematic approach for the computer-based damage assessment system.

In addition, attempts have been made to find special features in dynamic response records relating to structural damage [13,14]. Interstory force-deformation relations for two 10-story one-tenth scale reinforced concrete frames under repeated earthquake loading conditions were identified [13]. Toussi et al, also applied the theory of evidence to analyze these resulting hysteresis for the purpose of damage assessment [14].

5. Concluding Remarks

Following the construction of an important structure, it is desirable for structural engineers to make periodic inspections. Results of such inspections should be interpreted in terms of structural safety upon which a decision can be made as to whether and how the structure should be repaired. A number of publications on this subject matter have been reviewed and discussed herein. Because the failure behavior of any existing structure is too complex to be modelled mathematically in a precise manner, it is necessary to use expert opinion in the decision-making process. It is also desirable at present to develop interactive rule-based systems. These methods can be extended for application to nuclear structures. Meanwhile, studies are being made concerning dynamic testing of as-built nuclear power plants (e.g. [32]). Results of such tests and/or recorded response data for these structures during wind storms or earthquakes can be useful inputs for a damage assessment system such as the SPERIL-I [8]. Nevertheless, further research is required for such applications in engineering practice.

In this paper, only the assessment of structural safety at the time of inspection is discussed. It is indeed important to continue research activities for the estimation of structural reliability involving future loading conditions including random vibration studies and first-passage probability analysis which are covered by other authors during this conference.

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References

- [1] Freudenthal, A.M., "Safety of Structures," Transactions, ASCE, 112 115-180 (1947).
- [2] Freudenthal, A.M., Garrelts, J.M., and Shinozuka, M., "The Analysis of Structural Safety," Journal of the Structural Division, ASCE, 92, (ST1) 267-325 (February 1966).
- [3] Task Committee on Structural Safety, "Structural Safety--A Literature Review," Journal of the Structural Division, ASCE, 98 (ST4) 845-884 (April 1972).
- [4] Yao, J.T.P., "Damage Assessment and Reliability Evaluation of Existing Structures," Journal of Engineering Structures, 1 245-251 (October 1979).
- [5] Liu, S.C. and Yao, J.T.P., "Structural identification Concept," Journal of the Structural Division, ASCE, 104 (ST12) 1845-1858 (December 1978).
- [6] Hart, G.C., and Yao, J.T.P., "System Identification in Structural Dynamics," Journal of the Engineering Mechanics Division, 103 (EM6) 1089-1104 (December 1977).
- [7] Bresler, B., "Evaluation of Earthquake Safety of Existing Buildings," Developing Methodologies for Evaluating the Earthquake Safety of Existing Buildings, University of California, at Berkeley, UCB/EERC-77/06, 1-15 (February 1977).
- [8] Ishizuka, M., Fu, K.S., and Yao, J.T.P., "SPERIL: An Expert System for Damage Assessment of Existing Structures," Proceedings, The 6th International Conference on Pattern Recognition, Munich, Germany, (18-22 October 1982).
- [9] Wiggins, J.H., Jr., and Moran, D.V., Earthquake Safety in the City of Long Beach Based on the Concept of Balanced Risk, J.H. Wiggins Company, Redondo Beach, CA, (September 1971).
- [10] Culver, C.G., Lew, H.S., Hart, G.C., and Pirkham, C.W., Natural Hazards Evaluation of Existing Buildings, National Bureau of Standards, Building Science Series No. 61 (January 1975).
- [11] Bresler, B., and Hanson, J.M., "Damageability and Reliability of Existing Structures," Proceedings, Ninth U.S. National Congress of Applied Mechanics, ASME, 309-313 (21-25 June 1982).
- [12] Yao, J.T.P., "Reliability of Existing Structures," Reliability and Safety of Pressure Components, ASME, PVP-62, Edited by C. Sundararajan, 65-75 (June 1982).

- [13] Yao, J.T.P., Toussi, S., and Sozen, M.A., "Damage Assessment From Dynamic Response Measurements," Proceedings, Ninth U.S. National Congress of Applied Mechanics, ASME, 315-322 (21-25 June 1982).
- [14] Toussi, S., and Yao, J.T.P., "Assessment of Structural Damage Using the Theory of Evidence," Structural Safety, 1 107-121 (1982-1983).
- [15] Shin, O., Nakata, S., Kitagawa, Y., Yoshimura, M., and Kaminosono, T., A Progress Report on the Full-Scale Seismic Experiment of a Seven Story Reinforced Concrete Building - Part of the US-Japan Cooperative Program, ISSN 0453-4972, B.R.I. Research Paper No. 94, Building Research Institute, Ministry of Construction, Japan, (March 1982).
- [16] Oliveira, C.S., "Seismic Risk Analysis for a Site and a Metropolitan Area," University of California at Berkeley, EERC-75-3, (August 1975).
- [17] Yao, J.T.P., and Munse, W.H., "Low-Cycle Axial Fatigue Behavior of Mild Steel," ASTM Special Technical Publication, (338) 5-24 (1962).
- [18] Kasiraj, I., and Yao, J.T.P., "Fatigue Damage in Seismic Structures," Journal of the Structural Division, ASCE, 95 (ST8) 1673-1692 (August 1969).
- [19] Tang, J.P., and Yao, J.T.P., "Expected Fatigue Damage of Seismic Structures," Journal of the Engineering Mechanics Division, ASCE, 98 (EM3) 695-709 (June 1972).
- [20] Wiggins, J.H., Jr., and Moran, D.F., Earthquake Safety in the City of Long Beach Based on the Concept of Balanced Risk, J.H. Wiggins Company, Redondo Beach, CA, (September 1971).
- [21] Culver, C.G., Lew, H.S., Hart, G.C., and Pinkham, C.W., Natural Hazards Evaluation of Existing Buildings, National Bureau of Standards, Building Science Series No. 61, (January 1975).
- [22] Bresler, B., Okada, T., and Zisling, D., "Assessment of Earthquake Safety and of Hazard Abatement," Developing Methodologies for Evaluating the Earthquake Safety of Existing Buildings, UCB/EERC-77/06, University of California at Berkeley, 17-49 (February 1977).
- [23] Bertero, V.V., and Bresler, B., "Design and Engineering Decisions: Failure Criteria (Limit States)," Developing Methodologies for Evaluating the Earthquake Safety of Existing Buildings, UCB/EERC-77/06, University of California at Berkeley, 114-142 (February 1977).
- [24] Blejwas, T., and Bresler, B., Damageability in Existing Buildings, UCB/EERC-78/12, University of California at Berkeley, (August 1979).
- [25] Hasselman, T.K., and Wiggins, J.H., Earthquake Damage to High-Rise Buildings as a Function of Interstory Drift, Private Communication, (1982).
- [26] Instructions for Classification of Damage Level and Usability of Earthquake Damaged Structures, Institute of Earthquake Engineering and Engineering Seismology, University "Kiril and Methodij" - Skopje, Yugoslavia, (1979).
- [27] Kustu, O., Miller, D.D., and Brokken, S.T., Development of Damage Functions for High-Rise Building Components, JAB-10145-2, URS/John Blume & Assoc., San Francisco, CA, (October 1982).
- [28] Scholl, R.E., Kustu, O., Perry, C.L., and Zanetti, J.M., Seismic Damage Assessment for High-Rise Building, URS/JAB-8020, URS/John Blume & Assoc., San Francisco, CA, (July 1982).

- [29] Zadeh, L.A., "Fuzzy Sets," Information and Control, 8 338-353 (1965).
- [30] Brown, C.B., and Yao, J.T.P., "Fuzzy Sets in Structural Engineering," to appear in Journal of the Structural Engineering Division, ASCE, (1983).
- [31] Chameau, J.L.A., Altschaeffl, A.G., Michael, H.L., and Yao, J.T.P., "Potential Applications of Fuzzy Sets in Civil Engineering," to appear in Journal of Man-Machine Studies (1983).
- [32] Srinivasan, M.G., Kot, C.A., Hsieh, B.J., and Chung, H.H., Feasibility of Dynamic Testing of As-Built Nuclear Power Plant Structures: An Interim Evaluation, NUREG/CR-1937; ANL-CT-81-5, Argonne National Laboratory, Argonne, IL, (May, 1981).