COMPUTER-BASED ASSESSMENT OF SEISMIC DAMAGE

James T. P. Yao (I)
Presenting Author: James T. P. Yao

SUMMARY

Several approaches for the assessment of seismic damage are reviewed herein. Specifically, the current version of the computer-based system for the assessment of structural damage called SPERIL-I is described in this paper. To formulate the problem, the approach of production system is used to decompose a complex problem into a number of simpler sub-problems, the relations among which are either hierarchical or parallel. To acquire knowledge from human experts, these sub-problems are fitted to knowledge units of selected experts. Several improvements being implemented are discussed herein.

INTRODUCTION

Following each strong-motion earthquake, it is necessary for engineers to inspect damaged buildings and to decide whether particular buildings should be repaired or demolished. In such cases, a series of nondestructive evaluation techniques may be applied and the resulting data can be analyzed accordingly. Such data can range from the size, number, and location of cracks to the time-history of recorded ground motions and structural response in the form of accelerograms. To-date, relatively few structural engineers have sufficient experience and ability to interpret such measured data and calculated results in terms of meaningful damage evaluations.

The structural and fire evaluation model (SAFEM) was developed to provide a broad overview of potential safety problems for more than 10,000 buildings for a governmental agency in the States (Ref. 4). A building can be classified into (a) "green" requiring only routine scrutiny, (b) "yellow" requiring some attention, and (c) "red" requiring immediate attention and improvement. The procedure consists of (i) collection of such data as building size, cost, number of occupants, address, and predetermined exposure to natural hazards; (ii) ranking buildings on the basis of priorities; (iii) choosing buildings which should undergo field surveys; (iv) performing field surveys and recording survey results in the computer file; (v) re-ranking buildings on the basis of priorities and requesting engineering studies for buildings with the largest potential problems, (vi) performing engineering studies and producing the final priority rankings, and (vii) allocating funds for upgrading these structures following these priorities. A detailed computer program is developed on the basis of professional experience to combine

(I) Professor of Civil Engineering, Purdue University, West Lafayette, IN, USA

numbers ranging from 0 to 9 for hazards (geophysical, intrinsic, and local), exposure, and vulnerability. The SAFEM profiles include one each on fire, structural, and miscellaneous (glass safety, cladding failure, electrical system, elevator system, etc.). Although this program covers a broad scope and many detailed considerations, it is difficult to understand how the many subjective inputs are analyzed and summarized.

Several recent damage assessment studies are reviewed in a comprehensive manner by Scholl et al. (Ref. 5), who recommended a general procedure. By computing the maximum floor responses, they estimate the component damage by using a component motion-damage library (Ref. 6). The damage to a structure is defined as the sum of the component damage which in turn are sums of sub-component damage.

Recently, Hart et al. (Ref. 7) proposed the use of reliability indices for the evaluation of structural damage. FitzSimons (Ref. 8) also suggested the use of two techniques with the use of statistics and uncertainties.

Using information as found in historical documents on the Boston Old State House, Luft and Whitman (Ref. 9) estimated an upper bound for the peak ground acceleration of the 1755 Cape Ann earthquake using structural analysis techniques. They developed a structural model, with which a structural analysis was made on the basis of historical records. The levels of base acceleration was predicted and correlated with the damage record.

Sues et al. (Ref. 10) presented a method for the safety evaluation of structures subjected to earthquake hazards. A seismic hazard model is used to calculate the probabilities of all relevant ground motions over a specified time period. Moreover, a hysteretic structural model is used to calculate the required statistics of its random response to these expected earthquakes. The uncertainties in structural modeling and ground motions are considered in the calculation of conditional probabilities of damage for given earthquake intensities. These conditional probabilities are then combined with appropriate seismic hazard probabilities to obtain the desired probability of structural damage.

Recently, Moses and Yao (Ref. 11) summarized the general practices of structural engineers in the design, inspection, and redundancy implementation of buildings and bridges. They concluded that the actual behavior and reliability of structural systems remain to be studied.

Because (a) proprietary information is involved and (b) the real-world problems are still too complex to be completely understood, only general investigative procedures and obvious case histories are described in the open literature. Several proposed methodologies are reviewed herein. It is necessary to interpret available information in order to obtain meaningful results from using these methods. It seems that more work is needed to make these methods useful in practical sense. It is also desirable to compare results of applying different methods to a few

standard structures such that these methods can be calibrated with one another (Ref. 12). Eventually, it is desirable to develop a series of safety evaluation procedures for various types of structures under different circumstances. These and other methods can be included as parts of an expert system, which is described herein.

EXPERT SYSTEM

In reading proprietary reports concerning structural damage investigations, the writer usually understood the detailed description of the structure, available inspection results and test data, and methods and results of analysis. However, it is difficult to understand how the investigator(s) summarized all these results to reach the concluding damage classification, which are meaningful but not clearly defined.

In 1979, Fu and Yao (Ref. 13) suggested the application of pattern recognition (Ref. 14). In knowledge engineering (Ref. 15, 16), artificial intelligence (AI) techniques are applied to solve complex problems in the real world. Because a system designed on the basis of knowledge engineering is intended to work as a human expert, it is often called an "expert system". Such a system consists of knowledge base and inference machine. A knowledge base is a storage in a computer, in which useful knowledge is stored in a stylized form suitable for the inference. An inference machine is a control process which deduces an answer from a given problem situation by using the knowledge stored in the knowledge base.

In the inference process, questions are issued to obtain additional information in case of need. Those procedures are analogous to, for example, medical diagnosis, in which a physician draws a conclusion by synthesizing many observed symptoms and his/her knowledge.

The present problem is to construct a rational decision-making system for confirming whether the hypothesis that "the structure is severely damaged" is (a) true or (b) more reasonable than other hypotehses on the basis of observations. The observations may come from (i) visual inspection at various portions of the structure, (ii) reading and analysis of accelerometer records during the earthquake, (iii) results of nondestructive testing, and (iv) data of loading tests before, during, and/or after the earthquake. Although (i) and (ii) are primarily considered in the system design eventually. Available features for damage classification from the visual inspection may include the detection of deformations and cracks in columns, beams, joints, floors, ceilings, external and internal walls, doors, windows, stairs, nonstructural partitions, utilities, elevators, etc. Features to be derived from the accelerometer records by using system identification techniques may include the change of natural frequency of the building vibration, the change of damping factor, the maximum interstory drift and the total energy absorption and dissipation during the earthquake. In addition, we should consider many other conditions regarding the structures, such as structural material, height or number of stories, areas of floors, shapes, soil condition and foundation,

the year that the building was built, building use, design parameters if available, existence of walls, experience of human inspector, etc. which are stored and utilized for the inference as reference data apart from inspection data.

Ishizuka et al. (Ref. 17) presented a methodology for the decomposition of a complex problem into a number of simpler sub-problems. To accomodate knowledge efficiently from human experts, these sub-problems are fitted into knowledge units of the experts.

For the inference procedure with uncertainty and fuzzy restriction, two statistical methods using Bayesian probability and Dempster and Shafer's probability are described elsewhere (Ref. 18). The process of fuzzy reasoning is an approximate process of the application which is compatible with human intuitions (Refs. 19, 20). The advantage of fuzzy reasoning as an inference process under the framework of the problem reduction method is that it can yield an approximate answer when statistical methods are not applicable. Statistical methods often require idealized assumptions such as the independence of evidences and the mutual exclusiveness and exhaustiveness of hypotehses.

Because the fuzzy reasoning itself has no confirmation effect, it is desirable to generate combination rules and to add them to the knowledge base. With these inference procedures, the truth value propagates through the inference network and eventually the truth value of the hypothesis at the final goal is determined. The meaning of truth value or the degree of membership is vague in the physical sense, though it can be said that the higher the value is the more credible or possible the fact is. Note that the possibility is always larger than the credibility as defined herein.

A preliminary version of such a system called SPERIL-I has been developed for the purposes of illustration (Ref. 17). At present, it is being modified and expanded jointly at Purdue University and Wiss, Janney, Elstner and Associates (Ref. 21).

EVALUATION OF STRUCTURAL RELIABILITY

Any existing structure may have an initial value of "damage" in the broad sense. Certainly, there can be additional damage as results of unexpected usage of the structures, wear and corrosion, the occurrence of hazardous events, fatigue and other cumulative damage.

In this paper, 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.

To illustrate the fact that there are two types of problems in making safety evaluation of structures, we use the following classical reliability function (Ref. 22).

$$L_T(t) = L_T(0)\ e^{-\int_0^t h_T(t)dt} \tag{1}$$

where $h_T(t)$ is the hazard function. In the classical theory, the initial value for reliability, $L_T(0)$, is usually assumed to be 1.0. Suppose that the revised reliability following ith inspection is given as follows:

$$L_T^{(i)}(t) = L_T(t_i)\ e^{-\int_{t_i}^t h_T^{(i)}(t)dt} \tag{2}$$

where $L_T(t_i)$ can be considered as the updated estimate for the safety state of the particular structure at time t_i using inspection results and test data, and $h_T^{(i)}(t)$ is the updated hazard function.

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. 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. These definitions are reviewed elsewhere (Refs. 23-25).

Engineers usually like to manipulate numbers. Therefore, those definitions of structural damage with numerical values are appealing to many engineers. However, it appears that most numerical scales as used in the practice to-date are rather arbitrary. Those definitions involving repair or replacement costs are attractive on the surface. Nevertheless, questions remain as to the process with which such costs can be determined rationally and accurately without the precise knowledge on the extent of structural damage. The verbal classifications are meaningful, especially if and when such classifications are made by highly qualified experts. Nonetheless, there exist cases when numerical values are needed for further analysis of structural damage. As an example, if a particular structural member is severly damaged, how does it effect the damage state of the entire structure? The rule-based approach as described in the previous section is promising especially with the use of a more reasonable safety measure.

Following Blockley (Refs. 26, 27) and Brown (Ref. 28), a safety measure, N, is defined as the negative logarithm (with base 10) of the probability of failure, i.e.,

$$N = -\log p_f \tag{3}$$

The most important advantage for such a safety measure is that it is directly related to the probability of failure in a meaningful manner. Furthermore, it can be determined both objectively (Ref. 22) and subjectively (Refs. 26-28). Such a safety measure can be related to verbal classifications in a meaningful way.

Combining Eqs. 2 and 3, we obtain

$$L_T(t_i) = 1 - 10^{-N_i} \tag{4}$$

where the subscript denotes the corresponding inspection from which this safety measure is estimated. Using results of structural analysis and design and available statistical data, the classical theory of structural reliability (Ref. 22) can be used to obtain an objective safety measure. With the application of fuzzy sets and fuzzy logic, such an objective safety measure can be fuzzified (Refs. 27, 28). Then, additional analyses and expert system can be used to consider inspection results and field test data to yield an up-dated safety measure, which along with cost data can help engineers to make rational recommendations for possible action. A similar procedure can be developed to modify and up-date the mathematical hazard function (e.g., Refs. 1, 10, 29).

It is believed that the expert system can be useful in combining results of various analyses and approaches as reviewed herein. Moreover, the theory of evidence (e.g., Refs. 30, 31) can be applied to provide additional inputs to such an expert system.

CONCLUDING REMARKS

In this paper, an attempt is made to apply the theory of structural reliability for the safety evaluation of existing structures. The rule-based system for the evaluation of damage assessment called SPERIL-I is reviewed herein. Constructive suggestions for the improvement of this system are outlined and discussed. It is believed that the approximate evaluation of the safety measure as suggested by Brown (Ref. 28) is useful and meaningful because it can be directly related to structural reliability. The expert system as studied by Ishizuka et al. (Refs. 17, 18) can be extended and modified for such an evaluation. Moreover, it is desirable to evaluate and modify the hazard function which includes the effect of future loading and environmental conditions in a similar manner.

This study is supported in part by the National Science Foundation. Ms. Molly Harrington capably typed this manuscript.

REFERENCES

1. Rudd, J.L., Yang, J.N., Manning, S.D., and Yee, B.C.W., "Damage Assessment of Mechnically Fastened Joints in the Small Crack Size Range," Proceedings, Ninth U.S. Congress of Applied Mechanics, ASME, 1982, pp. 329-338.

2. Berens, A.P., Gallagher, J.P., and Hovey, P.W., "Statistics of Crack Growth," Proceedings, Ninth U.S. Congress of Applied Mechanics, ASME, 1982, pp. 325-328.

3. Guedelhoefer, O.C., "Methods for Strength Evaluation of Distressed Structures," Probabilistic Methods in Structural Engineering, Edited by M. Shinozuka and J.T.P. Yao, ASCE, 1981, pp. 327-343.

4. Bresler, B., Hanson, J.M., Comartin, C.D., and Thomasen, S.E., "Practical Evaluation of Structural Reliability," Preprint 80-596, ASCE Convention, Florida, October 27-31, 1980.

5. Scholl, R.E., Kustu, O., Perry, C.L., and Zanetti, J.M., Seismic Damage Assessment for High-Rise Building, Report No. URS/JAB-8020, URS/John Blume & Assoc., San Francisco, CA, July 1982.

6. Kustu, O., Miller, D.D., and Brokken, S.T., Development of Damage Functions for High-Rise Building Components, Report No. JAB-10145-2, URS/John Blume & Assoc., San Francisco, CA, October 1982.

7. Hart, G.C., DelTosto, R., and Englekirk, R.E., "Damage Evaluation Using Reliability Indices," Probabilistic Methods in Structural Engineering, Edited by M. Shinozuka and J.T.P. Yao, ASCE, 1981, pp. 344-357.

8. FitzSimons, N., "Techniques for Investigating Structural Reliability," Probabilistic Methods in Structural Engineering, Edited by M. Shinozuka and J.T.P. Yao, ASCE, 1981, pp. 399-404.

9. Luft, R.W., and Whitman, R.V., "Earthquake Resistance of a Historical Building," Probabilistic Methods in Structural Engineering, Edited by M. Shinozuka and J.T.P. Yao, ASCE, pp. 308-326.

10. Sues, R.H., Wen, Y.K., and Ang, A.H-S., "Safety Evaluation of Structures to Earthquakes," Probabilistic Methods in Structural Engineering, Edited by M. Shinozuka and J.T.P. Yao, ASCE, 1981, pp. 358-377.

11. Moses, F., and Yao, J.T.P., Safety Evaluation of Buildings and Bridges," Technical Report No. CE-STR-83-24, School of Civil Engineering, Purdue University, W. Lafayette, IN 47907.

12. White, R.N., and Gergley, P., Private Communication, May 1983.

13. Fu, K.S., and Yao, J.T.P., "Pattern Recognition and Damage Assessment," Proceedings, Third ASCE EMD Specialty Conference, University of Texas, Austin, 17-19 September 1979, pp. 344-347.

14. Andrews, H.C., Introduction to Mathematical Techniques in Pattern Recognition, Wiley-Interscience, 1972.

15. Feigenbaum, E.A., "The Art of Artificial Intelligence. I. Themes and Case Studies of Knowledge Engineering," Invited Paper, Proceedings, International Joint Conference on Artificial Intelligence, 1977, pp. 1014-1029.

16. Fenves, S.J., Private Communication, 21 October 1977.

17. Ishizuka, M., Fu, K.S., and Yao, J.T.P., "Rule-Based Damage Assessment System For Existing Structures," Solid Mechanics Archives, Martin Nijhoff Publishers, The Netherlands, 1983, pp. 99-118.

18. Ishizuka, M., Fu, K.S., and Yao, J.T.P., Inference Procedure with Uncertainty for Problem Reduction Method, Technical Report CE-STR-81-24, School of Civil Engineering, Purdue University, August 1981.

19. Zadeh, L.A., "Fuzzy Sets," Information and Control, 8, 1965, pp. 338-353.

20. Brown, C.B., and Yao, J.T.P., "Fuzzy Sets in Structural Engineering," Journal of Structural Engineering, ASCE, Vol. 109, No. 5, May 1983, pp. 1211-1225.

21. Ogawa, H., Fu, K.S., Hanson, J.M., and Yao, J.T.P., An Extension of Structural Damage Assessment System SPERIL-I, Technical Report CE-STR-83-4, School of Civil Engineering, Purdue University, 1983.

22. Freudenthal, A.M., Garrelts, J.M., and Shinozuka, M., "the Analysis of Structural Safety," Journal of the Structural Division, American Society of Civil Engineers, Vol. 92, No. ST1, 1966, pp. 267-325.

23. Liu, S.C., and Yao, J.T.P., "Structural Identification Concept," Journal of the Structural Division, ASCE, Vol. 104, N. ST12, 1978, pp. 1845-1858.

24. Yao, J.T.P., "Assessment of Seismic Damage in Existing Structures," Proceedings, U.S.-S.E. Asia Symposium on Engineering for Natural Hazard Protection, Edited by A.H-S. Ang, Manila, Philippines, 1977, pp. 383-399.

25. Yao, J.T.P., "Damage Assessment and Reliability Evaluation of Existing Structures," Engineering Structures, England, Vol. 1, October, 1979, pp. 245-251.

26. Blockley, D.I., "The Role of Fuzzy Sets in Civil Engineering," Fuzzy Sets and System, Vol. 2, 1979, pp. 267-278.

27. Blockley, D.I., The Nature of Structural Design and Safety, Ellis Horwood Ltd., Chichester, England, 1980.

28. Brown, C.B., "A Fuzzy Safety Measure," Journal of Engineering Mechanics Division, ASCE, Vol. 105, October 1979, pp. 855-872.

29. Yang, J.N., and Shinozuka, M., "On the First-Excursion Probability in Stationary Narrow-Band Random Vibration," Journal of Applied Mechanics, ASME, I: Vol. 38, No. 4, Dec. 1971, pp. 1017-1022, II: Vol. 39, No. 3, Sept. 1972, pp. 733-737.

30. Yao, J.T.P., Toussi, S., and Sozen, M.A., "Damage Assessment from Dynamic Response Measurements," Proceedings, Ninth U.S. National Conference on Applied Mechanics, ASME, June 1982, pp. 315-322.

31. Toussi, S., and Yao, J.T.P., "Assessment of Structural Damage Using the Theory of Evidence," Structural Safety, Vol. 1, (1982/1983), pp. 107-121.