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APPLICATION OF FUZZY SETS IN EARTHQUAKE ENGINEERING

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16. Abstract (Limit: 200 words)

Recommendations concerning earthquake engineering research provided by a committee on the Alaska Earthquake are discussed, including: (1) improved earthquake resistant designs and better methods of structural analysis should be developed; (2) more data on strong-motion ground movements should be collected; and (3) more knowledge on tidal waves and improvement in the tidal wave warning system is needed. It is pointed out that before structural damage can be assessed, it must be defined. The Modified Mercalli Intensity Scale is discussed as an example of a descriptive classification system for structural damage. Although existing structures can be studied both experimentally and analytically whenever there are signs of distress, the study procedures are known to only a small number of engineers. Therefore, it is suggested that fuzzy sets be utilized in damage assessment. Preliminary formulations of elementary fuzzy set relations to the problem of damage assessment of existing structures are provided.

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APPLICATION OF FUZZY SETS IN EARTHQUAKE ENGINEERING

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1. Introduction

It is well known that strong-motion earthquakes frequently cause heavy damage to properties and loss of lives throughout the history of mankind. Although attempts have been made to predict earthquakes in recent years, the lack of certainty and short duration of warning time involved in such predictions are not yet effective in reducing property damage and saving human lives (e.g., see [1]). Therefore, it is necessary for engineers to take precautions to minimize the undersirable earthquake effects.

In the United States, the first building codes to enforce earthquake-resistant design was adopted in California following the 1933 Long Beach earthquake, during which several school buildings were damaged. Since then, much progress has been made in the subject area of earthquake engineering [2].

In 1969, the Committee on Earthquake Engineering Research of the National Research Council, National Academy of Engineering made a report to the National Science Foundation [3]. In 1978, another report was made to prepare for an implementation plan to reduce earthquake hazards [4]. Meanwhile, academic researchers met periodically to report on their current research projects in earthquake engineering [5]. Abstracts of all published papers and reports have also been collected and disseminated since 1972 [6].

As it is shown in Figure 1, earthquake engineering research is related to many established disciplines. Obviously, it is not possible to discuss all aspects of earthquake engineering in this study. The objectives of this paper are to (a) briefly review several aspects of earthquake engineering research. (b) discuss the possible application of fuzzy sets in such studies in general, and (c) present a progress report on a research project dealing with safety evaluation of existing structures as an example of such applications.

2. Earthquake Engineering Research

A major impetus to earthquake engineering research was provided with the 1964 Alaska earthquake [7] during which the lack of earthquake engineering research efforts was vividly demonstrated. In 1969, a committee on the Alaska Earthquake made the following recommendations concerning earthquake engineering research [8]:

(a) Improved earthquake-resistant designs and better methods of structural analysis should be developed.

(b) Improved regulatory systems for control of design and construction in seismically active areas are needed.

(c) Major dams, reservoirs, storage tanks, and old buildings should be reappraised periodically for the identification and reduction of hazards of existing structures.

(d) More data on strong-motion ground movements should be collected.

(e) More knowledge on tidal waves and improvement in the tidal-wave warning system are needed.

(f) Earthquake-hazard maps are needed for all densely populated seismic areas.

These recommended research programs are in agreement with a subsequent report of the Committee on Earthquake Engineering Research [3]. Other recommended

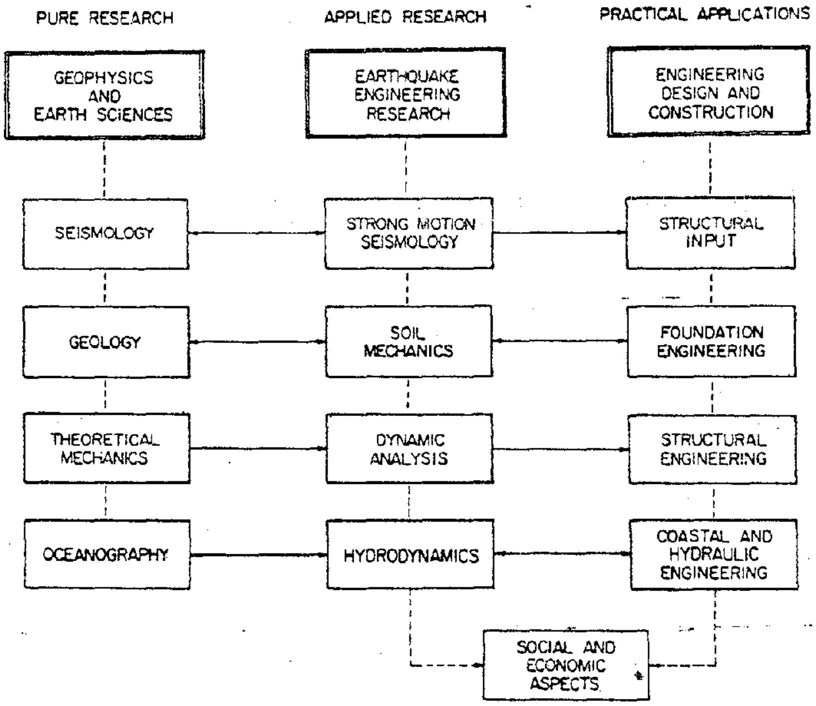

Figure 1 Relations among pure research, applied research, and practical applications [3]

studies deal with socio-economic aspects of earthquakes which are not discussed in this paper.

The basic problem of earthquake-resistant design is to determine (a) the shape, size and material of various structural elements, and (b) the method of fabrication and construction, so that the structure will perform its function satisfactorily. The preliminary stage of the design process requires professional creativity as well as a broad knowledge of the seismic behavior of structures. Detailed computations and design decisions are then conducted in an iterative manner until the final design of the structure is obtained. The design can be evaluated by computing the response of the structure to a given earthquake excitation.

In the United States, ordinary buildings are designed to survive (a) moderate earthquakes without significant damage, and (b) strong-motion earthquakes without collapse due to economic considerations. To-date, the dynamic properties of real structures under large deformations are not well-understood. Therefore, it is difficult to design structures for controlled damage. After the 1964 Alaska earthquake, accelerographs have been installed in many buildings in California to record the earthquake induced vibrations. Such recorded data have been useful in the development of better procedures for the design and analysis of aseismic structures. However, many problems remain in the analysis and interpretation of such data [9].

Building codes usually specify the acceptable minimum strength of structures, which are established with a consensus of engineers and officials of building departments. In a competitive society, the minimum specifications tend to become the standard practice.

Occasionally, deficiencies of codes are revealed by unsatisfactory performance of structures and thus lead to subsequent improvements. Because strong-motion earthquakes occur rather infrequently, the need for the improvement of seismic provisions in building codes is intermittent and progress due to experience is slow at times.

A major difficulty in earthquake engineering analysis and design is that most civil engineering structures are individually designed and built. In other words, many widely different types of structures must be considered. As an example, the San Francisco Bay Area Rapid Transit System sub-bay traffic tube between San Francisco and Oakland is a very much different structure from that of a tall building. Even among tall buildings, the configuration, material, and design details can be quite different from one to another. Conceptually, it should be possible to determine the mathematical representation of structural systems when the structural configuration and material properties are known. In practice, however, there are still difficulties in the determination of precise equations of motion in highly nonlinear regions where severe damage occur. During these past two decades, system identification techniques have been applied to obtain more realistic mathematical models of various civil engineering structures [10-15].

While we need to further develope structural applications of system identification techniques for highly nonlinear behavior, it is believed that the identification of other structural characteristics such as the damage state and some other reliability measure should be studied [16]. Recently, destructive and dynamic full-scale tests were conducted on an eleven-story reinforced concrete building [17] and a three-span steel highway bridge [18]. Such full-scale destructive test data are considered to be very important in the eventual development of a more rational approach for the damage assessment of existing structures [19].

It is well known that earthquakes which originate under the ocean can cause tidal waves (tsunamis) to submerge a coastal area and possible destroy man-made structures. Earthquake ground motions and earthquake-caused landslides have also produced destructive waves in lakes, reservoirs, and rivers. Whenever a destructive water wave strikes, there is a great potential for losses of human lives and valuable properties. Because of the need for cooling water, nuclear power plants are often built near a river, lake, or ocean and thus are exposed to the hazard of tidal waves.

For design purposes, it is desirable to prepare maps showing the expected ground motion (e.g., nature, frequency, and intensity of ground shaking) for each location. Available maps show that the whole country is divided into several zones of certain intensity of ground shaking. Further improvements in these maps can be made to include the consideration of the proximity of faults, local geology, the likelihood of permanent ground displacements, the potential of landslides and soil liquefaction within each seismic zone and even for specific sites. To-date, it is still difficult to produce seismic maps with such detailed information.

3. Possible Applications of Fuzzy Sets

In the above section, several topics in earthquake engineering research are outlined. It is noted that the desirable goals are frequently stated in linguistic terms. As an example, the basic design philosophy in the United States to-date is that ordinary buildings should survive (a) moderate earthquakes without significant damage and (b) strong earthquakes without collapse. Such words as moderate (and strong) and significant damage are meaningful but not precisely defined. Even the word "collapse" can be used meaning partial or total collapse. Although recorded earthquake data can be presented with many digits in a numerical form, their analysis and interpretation are not always precise and clear.

In the theory of pattern recognition [20,21], data are collected from a physical system such as an existing building structure. A set of features is then extracted from the input data, and then a classifier is applied to obtain the classification. In 1979, Fu and Yao [22] considered the problem of damage assessment in terms of pattern recognition. Similarly, such techniques can be applied to prepare seismic zoning and intensity maps.

In all of these applications, there exist uncertainties as well as ambiquities which must be considered in the process of obtaining a rational decision-making procedure. Since 1965, Zadeh has presented the theory of fuzzy sets [23,24]. Since then, it has been applied not only to engineering fields but also to wide range fields, such as economics, management science, artificial intelligence, psychology, linguistics, information retrieval, medicine, etc. [25]. In civil and structural engineering, several papers have appeared recently dealing with the application of fuzzy algorithm [26-28]. It is generally agreed that the fuzzy sets theory is a particularly useful tool dealing with problems which are represented in linguistic expressions related strongly to human subjectivity. In the following, a specific example is given on the damage assessment or safety evaluation of existing structures [28].

4. Damage Assessment of Existing Structures

Following a major earthquake, a few structures may suffer severe damage or collapse which are obvious to everyone involved. A great majority of structures, however, usually remain standing with various degrees of damage which may or may not be directly measurable or detectable. It is important to classify these existing structures according to their respective damage states so that appropriate decisions can be made to repair some or demolish a few others.

In order to assess structural damage, it is necessary to first define it. The Modified Mercalli Intensity (MMI) scale [2] is an example of such a descriptive classification of structural damage. In studying the building damage resulting from the Caracas Earthquake of 29 July 1967, Seed *et al* [29] used several quantities for the description of the damage state of buildings. For each individual building, the ratio of maximum induced dynamic lateral force to static design lateral force is used for brittle structures, and the ratio of spectral velocity to lateral force coefficient is used for ductile structures. Shinozuka and Kawakami [30] reported on the use of a "leakage damage index" in studying the earthquake damage of Japanese underground pipeline systems. This index is given as the ratio of the number of pipe breakages to the length (in km) of the pipelines in each area.

In the 1971, Wiggins and Moran [31] suggested a procedure for grading existing building structures in Long Beach, California. Later, Whitman et al [32] defined several damage states for use in a damage matrix to evaluate the damageability of various classes of buildings. In an application in estimating structural damage due to tornadoes, Hart [33] gave six classifications as "none", "light", "moderate", "heavy", "very severe", and "collapse" on the bases of the ratio of repair cost to replacement cost for the entire structure. Hsu et al [34] used a similar scale in their study of seismic risks in 1976. Recently, Whitman et al [35] studied two specific buildings in Boston to evaluate their as-built resistance using four categories of damage state, namely, none or minor, slight or moderate, serious, and total damage. Housner and Jennings [36] used classifications such as minor, moderate, severe, major damage, and partial collapse. A similar classification system is recommended in a publication of the Earthquake Engineering Research Institute [37]. When the theory of fuzzy sets is applied, any such damage classification can be used with suitable membership functions.

As a continuous scale, Blume and Monroe [38] assumed damage to be linearly related to ductility factor with "0" denoting elastic behavior and "1" denoting total collapse of the structure. Bertero and Bresler [39] 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. Bresler [40] 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 [41] defined a damage ratio which may be considered as a special case of an earlier model for axially-loaded mild steel specimens subjected to low-cycle high-amplitude reversed plastic deformations [42].

Aristizabal-Ochoa and Sozen [43] used a damage ratio in the substitute-structures method, with which the inelastic response of the structure can be considered by using a linear dynamic analysis.

Culver et al [44] presented the field evaluation method in which a rating of 1 through 4 is assigned for each of the following items: geographic location, structural system, and nonstructural system. Then a composite rating is computed according to a given formula and the building is evaluated accordingly. Bresler, Okada and Zisling [45] commented that this algebraic formulation is arbitrary, and that too much weight is given for present condition and too little weight is assigned to quantity rating. It appears that the theory of fuzzy sets can be useful in the improvement of such a method.

In 1977, a safety evaluation program was developed [46]. Subjective evaluations are obtained for exposure, vulnerability, and combined safety index. A digital scale of 0 through 9 is used with 0 denoting non-impact and 0 denoting severe impact. Weighting factors are then applied to obtain a combined index for safety evaluation.

Bertero and Bresler [39] presented damageability criteria according to local, global, and cumulative damage using the summation operation. An importance factor is introduced for each element depending upon such considerations as life hazard and cost. Recently, Blejwas and Bresler [47] developed this method further by giving more detailed procedures.

Lee and Collins [48] developed a systematic methodology for the determination of risk for structures due to fire, flood, earthquake, wind hazards. The risk equiation was used to obtain an estimate the average annual loss. In this study, the damage was represented by percent of replacement value of the structure.

As a structure undergoes various degrees of damage, certain characteristics have been found to change. Wang, et al tested a reinforced concrete shear wall under reversed loading conditions, and performed free vibration tests to estimate the fundamental natural frequency and damping ratio [49]. Results of these tests indicate that (a) the frequency decreased monotonically with damage while the damping ratio increased initially and then decreased, and (b) the reparied specimen was not restored to the original condition as indicated by free-vibration test data. Similar results were reported by Hudson [11], Hilgardo and Clough [50], and Aristizabal-Ochoa and Sozen [43].

In 1978, comprehensive experimental results of dynamic full-scale tests were obtained for a multi-story building structure [17] and a 3-span highway bridge [18]. Galambos and Mayes [17] tested a rectangular 11-story reinforced concrete tower structure. Test results indicate that the natural frequency decreased with increasing damage in general. Similarly, Baldwin et al [18] concluded from their testing of a three-span continuous composite bridge that changes in the bridge stiffness and vibration signitures can be used as indicators of structural damage under repeated loads.

In current practice, an existing structure can be studied both experimentally and analytically whenever there are signs of distress or periodic inspection procedure is applied [51,52]. Experimental studies include either field surveys or laboratory tests. Field surveys include the determination of exact locations of failed components and other evidence of distress, the application of various nondestructive testing techniques to the remaining structure, the discovery of poor workmanship and construction details, and proof-load and other load testing of a portion of a very large structure. Meanwhile, samples can be collected from the field and tested in the laboratory for strength and other mechanical and structural properties. Analytical studies frequently consist of the examination of the original design calculations and drawings, the review of project specifications, the performance of additional structural analyses incorporating field observations and test data, and the possible explanation and description of the event under consideration. Although such general procedures as known to exist, the detailed methodology, especially the decision making process, remain as priviledged information for a relatively few and are being transmitted to younger engineers primarily through experience and "intuition".

It appears to be timely to apply the theory of fuzzy sets to obtain a rational solution of this problem. To-date, only the elementary algebra of fuzzy sets is applied [28]. An attempt is also being made to introduce such a concept and methodology to more civil engineers who are interested in earthquake engineering research.

As more specific examples of such an application, Yao [28] applied elementary fuzzy relations to the complex problem of damage assessment of existing structures. These preliminary formulations are given in Appendix A for the purpose of illustration.

5. Summary and Discussions

In this paper, an attempt is made to review several aspects of earthquake engineering research and to discuss the possible application of fuzzy sets in such studies. In addition, a progress report is presented on a research project concerning the safety evaluation of existing structures which are usually complex systems.

It is hoped that this paper will serve the purpose of introducing the problems of earthquake engineering to experts of fuzzy sets so that some of you will collaborate with other structural engineers to further develope such applications. Meanwhile, efforts are being made to stimulate interest among structural engineers to study the theory of fuzzy sets for such purposes.

APPENDIX A: AN EXAMPLE FORMULATION [28]

A.1 General Remarks

Recently, Fu and Yao [22] considered the problem of damage assessment in the context of pattern recognition [20,21]. The theory of pattern recognition is the study of mathematical techniques to build machines to aid human experience [20]. Essentially, the process of pattern recognition can be illustrated in a schematic diagram as shown in Figure A1. The physical world consisting of infinite dimensions are measured through the use of transducers to produce a measurement space with m dimensions. These measurements are then analyzed to obtain a feature space with n(<m) dimensions. Finally, a classifier is needed to yield the desired classification.

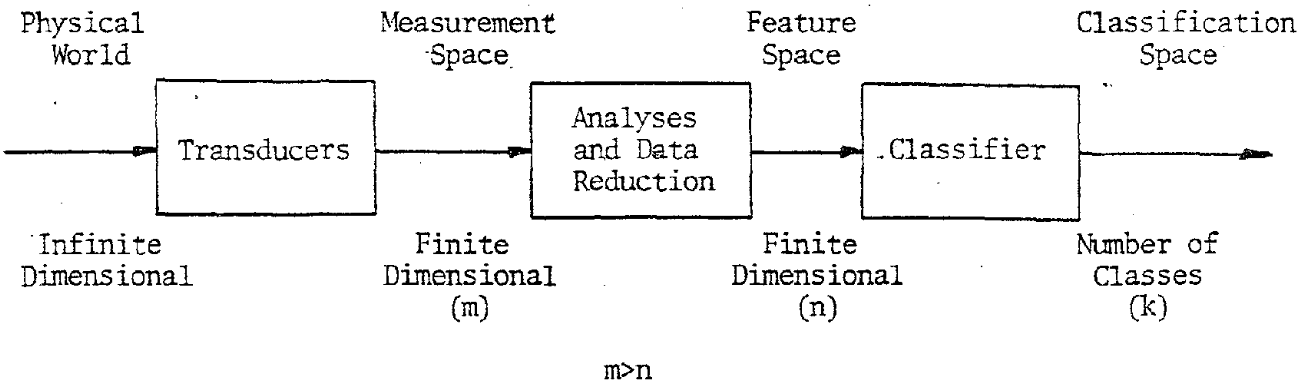

Figure A1. Schematic Diagram of Pattern Recognition

In general, data are collected from the inspection and testing of an existing building structure with the use of transducers. Such data may include (a) the size, number, and location of cracks, and (b) time-history of measured ground motions and structural response in the form of accelerograms. An example of crack patterns is given by Sozen et al [43]. Data such as accelerograms can be analyzed to extract a pattern or feature space. As examples, several methods have been developed for the estimation of the changing natural frequency using records of ground motions and structural response during a given earthquake. In the following, an attempt is made to formulate a decision function or classifier for the determination of the damage state on the basis of the resulting pattern space.

A.2 Classifiers

In general, there are two types of data from the inspection and testing of the structure. One type of observations is made from local phenomena such as cracks in certain structural members. Such information can be incorporated in a logical manner to obtain an estimate of the damage state of the whole structure. The other type of data are taken from global behavior of the structure such as the structural response and ground-motion records.

Let B denote the event that the whole structure has been severely damaged, and B_i denote the severely-damaged state of the structure using ith group of data. For example, i=1 corresponds to the information on detected cracks in the structure, and i=2 corresponds to the features extracted from recorded accelerograms. Therefore, for m groups of data, we have,

$$B = \bigcup_{i=1}^{m} B_i \qquad \text{(A1)}$$

or,

$$\mu_B = \underset{i}{V}(\mu_{B_i}) \tag{A2}$$

Furthermore, for ith group of data which are related to the jth component of the structure consisting of a total of n components, let D_{ij} denote the severely-damaged state of the jth component. Then B_i can be considered as the algebraic sum of the damage of each component, i.e.,

$$B_i = \sum_{j=1}^{n} D_{ij} \tag{A3}$$

or

$$\mu_{B_i} = 1 - \prod_{j=1}^{n} [1 - \mu_{D_{ij}}] \tag{A4}$$

For the purpose of illustration as noted above, let B_1 denote the severely-damaged state of the structure from carck detection and measurements, and B_2 denote the severely-damaged state of the structure from a reduction of the natural (fundamental) frequency of the structure. Say that there are 3 major components with detected cracks, and we have $\mu_{D_{11}} = 0$, $\mu_{D_{12}} = 0.8$, $\mu_{D_{13}} = 0.6$, then

$$\mu_{B_1} = 0.92 \tag{A5}$$

Meanwhile, we find that the calculated reduction of measured natural frequency is 25%. Through the use of an hypothetically established membership function, we obtain

$$\mu_{B_2} = 0.78 \tag{A6}$$

The determination of this membership can be based on full-scale destructive test data such as those of Galambos and Mayes [17] as shown in Figure A2 plus advice from various experts. Then, the membership of the structure in the severely-damaged state is given by

$$\mu_B = \max(\mu_{B_1}, \mu_{B_2}) = 0.92 \tag{A7}$$

As another possible approach, let $X = \{x_1, x_2, \ldots, x_k\}$ be a set of k features. For example, x_1 = many cracks, x_2 = large cracks, and x_3 = excessive deformation. Also, let $Y = \{y_1, y_2, \ldots, y_\ell\}$ be a set of ℓ potential failure modes. For example, y_1 = fatigue and fracture failure, y_2 = creep, y_3 = instability, and y_ℓ = progressive collapse. Furthermore, let Z = the severely-damaged state. If we can find the fuzzy relations R (from X to Y) and S (from Y to Z), we can relate features X to the severely-damaged state of the structure Z by taking the composition $R \bullet S$. For the purpose of illustration, let R and S be given as follows:

$$R = \begin{array}{l|cccc} & y_1\text{: Fatigue \& Fracture} & y_2\text{: Creep} & y_3\text{: Instability} & y_4\text{: Progressive Collapse} \\ \hline x_1\text{: many cracks} & 0.9 & 0.2 & 0.4 & 0.4 \\ x_2\text{: large cracks} & 0.8 & 0.3 & 0.7 & 0.8 \\ x_3\text{: excessive deformation} & 0.3 & 0.8 & 0.9 & 0.7 \end{array} \qquad \text{(A8)}$$

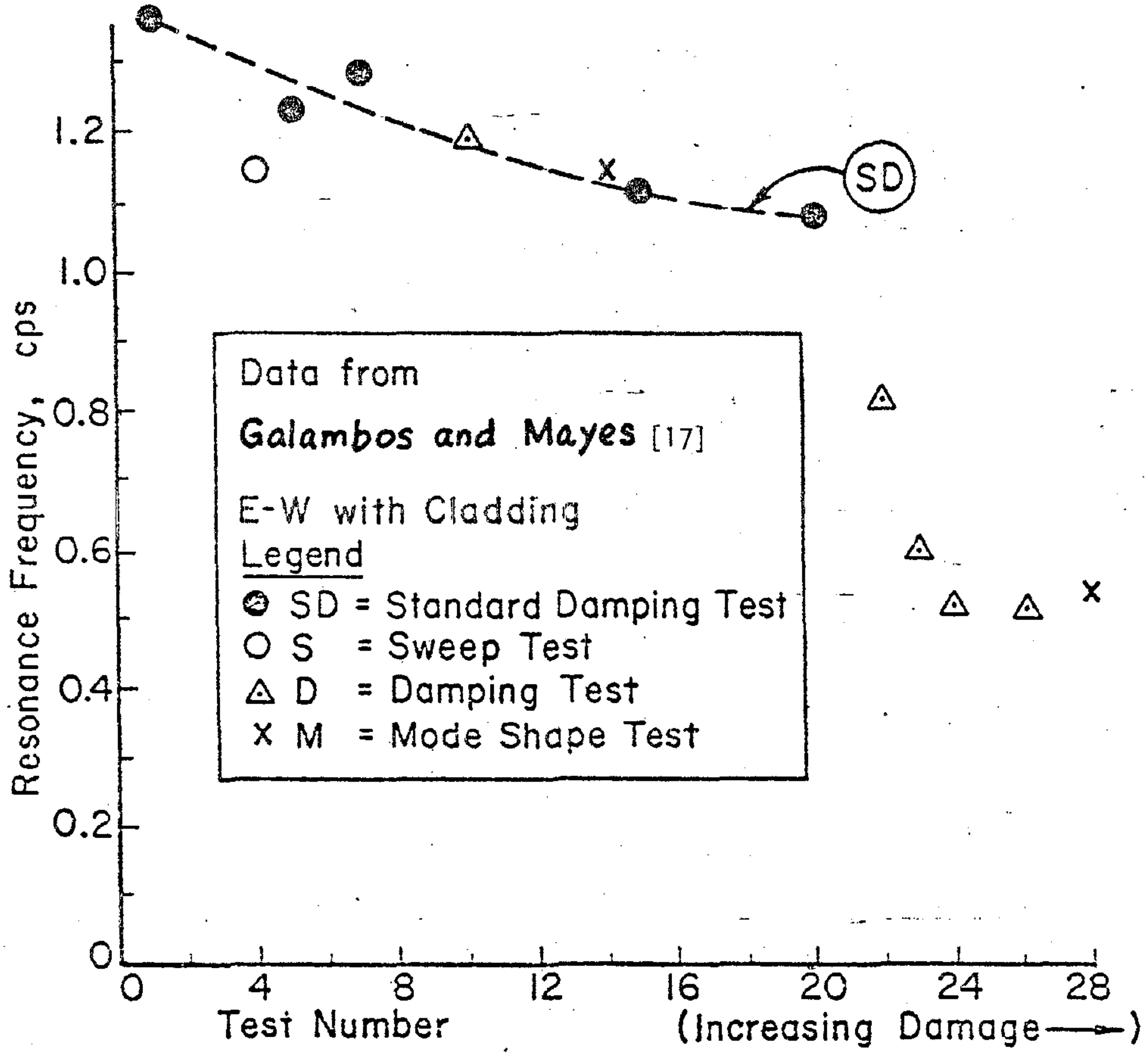

FIGURE A 2. VARIATION OF NATURAL FREQUENCY WITH A DAMAGE MEASURE

$$S = \begin{array}{c|c} & z \\ & \text{severely damaged} \\ \hline \begin{matrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{matrix} & \begin{bmatrix} 0.4 \\ 0.3 \\ 0.8 \\ 1.0 \end{bmatrix} \end{array} \tag{A9}$$

Then

$$R \bullet S = \begin{array}{c|c} & z \\ \hline \begin{matrix} x_1 \\ x_2 \\ x_3 \end{matrix} & \begin{bmatrix} 0.4 \\ 0.8 \\ 0.8 \end{bmatrix} \end{array} \tag{A10}$$

Results as given in Equation A10 indicate that the presence of features x_2 (large cracks) and x_3 (excessive deformation) would constitute a strong membership of the structure being in the severely damaged state. In other words, if large cracks and excessive deformations are present, the structure can be classified as being "severely damaged".

APPENDIX B: REFERENCES

[1] Jennings, P. C., Editor, Earthquake Engineering and Hazards Reduction in China, CSCPRC Report No. 8, National Academy of Sciences, Washington, D.C., 1980.

[2] Newmark, N. M., and Rosenblueth, E., Fundamentals of Earthquake Engineering, Prentice-Hall, Englewood Cliffs, NJ, 1971.

[3] Earthquake Engineering Research, Committee on Earthquake Engineering Research, National Academy of Sciences, Washington, D.C., 1969.

[4] Earthquake Hazard Reduction: Issues for an Implementation Plan, Working Group on Earthquake Hazards Reduction, Office of Science and Technology Policy, Executive Office of the President, 1978.

[5] Reports and Proceedings of the Universitites Council for Earthquake Engineering Research, California Institute of Technology, Mail Code 105-44, Pasadena, CA 91125.

[6] Abstract Journal in Earthquake Engineering, Earthquake Engineering Research Center, University of California at Berkeley, 47th Street and Hoffman Boulevard, Richamond, CA 94804, Vol. 1- , 1972-

[7] Wood, F. J., Editor, The Prince William Sound, Alaska, Earthquake of 1964 and Aftershocks, Coast and Geodetic Survey, U.S. Department of Commerce, Vol. I, 1966; Vol. II, Part A, 1967.

[8] Toward Reduction of Losses from Earthquakes, Committee on the Alaska Earthquake, National Academy of Sciences, Washington, D.C., 1969.

[9] Hart, G. C., Editor, Proceedings, MSF-UCLA Workshop on Stron-Motion Records from Buildings, Mechanics and Structures Department, UCLA, March 21 - April 2, 1980.

[10] Rodeman, R., and Yao, J. T. P., Structural Identification - Literature Review, Technical Report No. CE-STR-73-3, School of Civil Engineering, Purdue University, December 1973, 36 pages.

[11] Hudson, D. E., "Dynamic Tests of Full-Scale Structures", Journal of the Engineering Mechanics Division, ASCE, V. 103, N. EM6, December 1977, pp. 1141-1157.

[12] Hart, G. C., and Yao, J. T. P., "System Identification in Structural Dynamics, Journal of the Engineering Mechanics Division, ASCE, V. 103, N. EM6, Dec. 1977, pp. 1089-1104.

[13] Ting, E. C., Chen, S. J. Hong, and Yao, J. T. P., System Identification Damage Assessment and Reliability Evaluation of Structures, Technical Report No. CE-STR-78-1, School of Civil Engineering, Purdue University, February 1978, 62 pages.

[14] Yao, J. T. P., and Schiff, A. J., System Identification in Earthquake Engineering, Technical Report No. CE-STR-80-7, School of Civil Engineering, Purdue University, May 1980, 12 pages.

[15] Ibanez, P., et al, Review of Analytical and Experimental Techniques for Improving Structural Dynamic Models, Bulletin 249, Welding Research Council, New York, June 1979, 44 pages.

[16] Liu, S. C., and Yao, J. T. P., "Structural Identification Concept", Journal of the Structural Division, ASCE, V. 104, N. ST12, December 1978, pp. 1845-1858.

[17] Galambos, T. V., and Mayes, R. L., Dynamic Tests of a Reinforced Concrete Building, Research Report No. 51, Department of Civil Engineering, Washington University, St. Louis, MO, June 1978.

[18] Baldwin, J. W., Jr., Salane, H. J., and Duffield, R. C., Fatigue Test of a Three-Span Composite Highway Bridge, Study 73-1, Department of Civil Engineering, University of Missouri-Columbia, June 1978.

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

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

[21] Mendel, J. M., and Fu, K. S., Editors, Adaptive, Learning and Pattern Recognition Systems, Academic Press, 1970.

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

[23] Zadeh, L. A., "Fuzzy Sets", Information and Control, V. 8, 1965, pp. 338-353.

[24] Zadeh, L. A., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes", IEEE Transactions on Systems, Man and Cybernetics, V. SMC-3, N. 1, January 1973, pp. 28-44.

[25] Zadeh, L. A., Fu, K. S., Tanaka, K., and Shimura, M., Fuzzy Sets and Their Applications to Cognitive and Decision Process, Academic Press, 1975 (Proceedings of U.S. - Japan Seminar).

[26] Blockley, D. I., and Ellison, E. G., "A New Technique for Estimating System Uncertainty in Design", Proceedings, The Institution of Mechanical Engineers, London, Vol. 193, No. 5, 1979, pp. 159-168.

[27] Brown, C. B., "A Fuzzy Safety Measure", Journal of the Engineering Mechanics Division, V. 105, N. EM5, October 1979, pp. 855-872.

[28] Yao, J. T. P., "Damage Assessment of Existing Structures", Journal of the Engineering Mechanics Division, ASCE, Vol. 106, N. EM4, August 1980.

[29] Seed, H. B., Idriss, I. M., and Dezfulian, H., Relationships Between Soil Conditions and Building Damage in the Caracas Earthquake of July 29, 1967, Earthquake Engineering Research Center, University of California at Berkeley, Report No. EERC 70-2, February 1970.

[30] Shinozuka, M., and Kawakami, H., Underground Pipe Damage and Ground Characteristics, Technical Report No. CU-1, Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, NY, June 1977.

[31] 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, California, September 1971.

[32] Whitman, R. V., Reed, J. W., and Hong, S. T., "Earthquake Damage Probability Matrices", Proceedings, 5th World Conference on Earthquake Engineering, Rome, Italy, 1973.

[33] Hart, G. C., Estimation of Structural Damage, J. H. Wiggins Company, Los Angeles, CA, 1976.

[34] Hsu, D. S., Gaunt, J. T., and Yao, J. T. P., "Structural Damage and Risk in Earthquake Engineering", Proceedings, International Symposium on Earthquake Structural Engineering, Vol. 2, University of Missouri, Rolla, MO, 19-21 August 1976, pp. 843-856.

[35] Whitman, R. V., Heger, F. J., Luft, R. W., Krimgold, F., "Evaluation of Seismic Resistance of Existing Buildings", Preprint 3264, ASCE Spring Convention, Pittsburgh, PA, 24-28, April 1978.

[36] Housner, G. W., and Jennings, P. C., *Earthquake Design Criteria for Structures*, Report No. EERC 77-06, California Institute of Technology, Pasadena, CA, November 1977.

[37] *Learning from Earthquakes*, *1977 Planning and Field Guides*, Earthquake Engineering Research Institute, Berkeley, CA, 1977.

[38] Blume, J. A., and Monroe, R. E., *The Spectral Matrix Method of Predicting Damage from Ground Motion*, Report No. JAP-99-88, John Blume & Associates, 1971.

[39] Bertero, V. V., and Bresler, B., "Design and Engineering Decisions: Failure Criteria (Limit States)", *Developing Methodologies for Evaluating the Earthquake Safety of Existing Buildings*, Earthquake Engineering REsearch Center, University of California at Berkeley, Report No. UCB-EERC-77/06, February 1977, pp. 114-142.

[40] Bresler, B., "Behavior of Structural Elements--A Review", *Building Practices for Disaster Mitigation*, Edited by R. Wright, S. Kramer, and C. Culver, National Bureau of Standards, Building Science Series No. 46, February 1973, pp. 286-351.

[41] Oliverira, C. S., *Seismic Risk Analysis for a Site and a Metropolitan Area*, Report No. EERC-75-3, Earthquake Engineering Research Center, University of California, Berkeley, CA, August 1975.

[42] Yao, J. T. P., and Munse, W. H., "Low-Cycle Axial Fatigue Behavior of Mild Steel", *ASTM Special Technical Publication*, No. 338, 1962, pp. 5-24.

[43] Aristizabal-Ochoa, J. D., and Sozen, M. A., *Behavior of a Ten-Story Reinforced Concrete Walls Subjected to Earthquake Motions*, SRS No. 431, Department of Civil Engineering, University of Illinois, Urbana, Il, October 1976.

[44] 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.

[45] 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*, Earthquake Engineering Research Center, University of California at Berkeley, Report No. UCB/EERC-77/06, February 1977, pp. 17-49.

[46] Kudder, R., Private Communication, 20 April 1977.

[47] Blejwas, T., and Bresler, B., *Damageability in Existing Buildings*, Report No. UCB/EERC-78/12, Earthquake Engineering REsearch Center, University of California, Berkeley, CA, August 1979.

[48] Lee, L. T., and Collins, J. D., "Engineering Risk Management for Structures", *Journal of the Structural Division*, ASCE, V. 103, N. ST9, September 1977, pp. 1739-1756.

[49] Wang, T. Y., Bertero, V. V., and Popov, E. P., Hysteretic Behavior of Reinforced Concrete Framed Walls, Report No. EERC 75-23, Earthquake Engineering Research Center, University of California, Berkeley, California, December 1975.

[50] Hidalgo, P., and Clough, R. W., Earthquake Simulator Study of a Reinforced Concrete Frame, Report No. EERC 74-13, Earthquake Engineering Research Center, University of California, Berkeley, California, December 1974.

[51] Hanson, J. M., Private Communication, 11 June 1977.

[52] Bresler, B., "Evaluation of Earthquake Safety of Existing Buildings," Developing Methodologies for Evaluating the Earthquake Safety of Existing Buildings, Earthquake Engineering Research Center, University of California at Berkeley, Report No. UCB/EERC-77/06, February 1977, pp. 1-15.