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QUICK POST-EARTHQUAKE SAFETY EVALUATION OF BUILDINGS EQUIPPED WITH A NEW PC-BASED SEISMIC RECORDING SYSTEM

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ABSTRACT

The framework of a quick post-earthquake safety evaluation method for buildings equipped with a PC-based seismic recording system is outlined. The key component of this method, a system identification processor, is developed with the aid of an expert system to render the processor automated. With a pre-processor that defines all parameters necessary to start the computation and a post-processor to compute building behavior indices based on the results of system identification and to implement damage assessment based on criteria defined for the particular building, a completely automated safety evaluation based on measured acceleration data alone can be carried out within an hour or shorter of an earthquake event. The result of the safety evaluation will be useful for the building owner to make timely decision regarding actions to be taken in the wake of an earthquake.

KEYWORDS

Automated system identification; expert system; PC-based system; damage assessment.

INTRODUCTION

One of the major problems in post-earthquake building evaluation is the timely inspection of buildings for safety. A building may or may not appear to be damaged and the owner is eager to have a quick evaluation of the safety of the building. Even if expert engineers arrive quickly, mere eye inspection may not be sufficient to offer definitive conclusions on the safety of the building. Analysis of recorded motion of the building, which is installed with conventional type of seismometers, will also take too long a time to produce useful information for immediate decisions.

This undesirable situation is changed by the advent of a PC-based seismic recording system. It involves two PCs and a signal conditioner that automatically digitize and record the acceleration input from conventional accelerometers deployed throughout the building. One of the PCs can be utilized to do further work once the earthquake motion ceases. Thus, this new system offers the possibility of almost instant analysis of the recorded motion. The system is originally developed by U.S. scientists but found its first large scale deployment in Taiwan in more than forty buildings. Its robustness has been proven in several earthquakes in Taiwan in the last two years. Thus, automated recording of acceleration data in a form suitable for subsequent analysis is an achieved fact with such a PC-based system. The stage is then set for the development of an automated post-earthquake safety evaluation method that fully utilizes the advantages of this PC-based system.

FEASIBILITY STUDY

A prerequisite for an automated safety evaluation method using recorded acceleration data of a building is to have enough information contained in the acceleration record such that a damage assessment can be carried out using the recorded data. Here it must be stressed that by damage we mean structural damage which has a bearing on the safety of a building. In the past, although many buildings have been damaged by earthquakes, it is rare that an instrumented building is damaged. The recorded data of only a few damaged buildings are therefore very valuable for a feasibility study of the contemplated method. The 1979 record of the severely damaged Imperial County Service Building was studied for this purpose by Mau and Revadigar (1994). It was a six-story reinforced concrete (RC) building with moment resisting frames in the longitudinal, east-west (E-W), direction and shearwalls in the transverse direction. The columns at the east end of the ground story were severely damaged during the 1979 earthquake. The building was instrumented at the ground, the second, the fourth and the roof levels. Several findings are relevant to damage assessment. It was found that abnormal signals of high frequency (greater than 20 Hz) began to appear at 6.8 sec. of the uncorrected acceleration records of the roof, the fourth floor and the second floor. At 11.1 sec. the abnormal signals became prominent and they coincided with a large spike in the torsional motions of the roof and the second story.

A system identification was carried out for every three seconds of the time history. The first mode frequency in the E-W direction dropped from about 1.3 Hz at the beginning of the earthquake to about 0.65 Hz after the 6~8 sec. time window. Similar drops in the transverse first mode of vibration and the torsional mode were also found. The ground story relative drift in the E-W direction was about 0.7% at 7 sec. and reached a maximum of 1.5% at about 11.1 sec. From this brief summary, it was concluded that the coincidence of abnormal high frequency signals, large frequency changes, and large story drift ratios was the sign of structural damage. For this building, it was speculated that some damage may have incurred at 6.8 sec and the damage climaxed at about 11.1 sec when the east end columns at the ground story crushed.

In the same study, a more recent case was investigated. A seven-story RC frame building was reported to be severely damaged at the base and mid-elevation (EQE International, 1994) during the 1994 Northridge Earthquake. The building was instrumented at the ground, the second, the third, the sixth and the roof levels. Only corrected record was made available by the California Strong Motion Instrumentation Program at the time of the study. Thus, abnormal high frequency signals, if present would have been eliminated by the correcting process, were not found. The same system identification was performed using three-second time windows. The first frequency in the longitudinal (E-W) direction was found to change from about 0.85 Hz to 0.50 Hz after the 9~11 sec. window. The transverse frequency changed from about 1.1 Hz to 0.52 Hz. The torsional frequency also changed from close to 1 Hz to 0.48 Hz. Significantly, the same kind of change in frequency was found using a totally different system identification method (Loh and Lin, 1995). The E-W story drift ratio of the second story had a maximum of 1.94% at 8.54 sec. Again, the coincidence of large frequency change and story drift was the sign of structural damage. Furthermore, the same building was slightly damaged during the 1971 San Fernando Earthquake when the maximum story drift was estimated to be 1% (Blume, 1973). Thus, more than slight damage could be expected when the story drift was 1.9 % during the Northridge Earthquake.

From this study it was concluded that signs of damage were contained in the acceleration time history recorded during the earthquake. It would take a careful study of the record and an equally careful interpretation of the results of system identification to reach some degree of conclusion on damage.

AUTOMATED SYSTEM IDENTIFICATION

A major component in an automated safety evaluation method for buildings is automated system identification. System identification is mathematically an inverse problem in which the input and output to a system are known and the system equation or the parameters of an assumed system equation are to be found. Since it amounts to find the best match between the calculated data and the recorded data by adjusting the parameters, the solution to this inverse problem is often not unique. The solution process is also iterative in nature. While there are a variety of different system identification methods that can be applied to building seismic records, a least-square output error method based on modal superposition has been found practical for building record analysis (Li and Mau, 1991; Beck and Jennings, 1980). The structural model of this method is assumed to be a multi-degree-of-freedom discrete system of second order. The earthquake response of the system is obtained by superposing the dominant vibrational modes of the system. As the response is measured at several levels of a building and the ground motion consists of at least three major components, longitudinal, transverse and torsional ground floor motions, the system has multiple-input and multiple output (MIMO). The identification results are more reliable if all the output records are matched at once so that a single set of parameters are obtained as the solution to the inverse problem. Thus, this becomes a MIMO system identification problem. Since the real building characteristics may change during earthquake, this inherently linear system is to apply only over a short duration of time, within this time window the building system may be considered linear. The parameters of this system are obtained by minimizing the least square error iteratively. These parameters are representative of an equivalent linear system to the real building. By repeating the identification process over consecutive windows, the changing nature of the response can be followed as the parameters change from window to window.

The success of this identification process depends very much on the initial guess of the parameters. The iterative process may not converge or it may converge to a set of parameters that are outside of the bounds of physical sense, e.g. damping ratio being negative. Thus, repeated trials may be necessary before an acceptable set of parameters is obtained. To have an automated process for system identification means a set of criteria must be used to judge whether the system identification results are acceptable and if not, a new iteration cycle must be started automatically. Conceptually, the process of this automated system identification can be represented by the diagram shown in Fig. 1, under the heading of main-processor.

There are two ways to design the automated process. One is to write an algorithm to include all the criteria and action measures to execute the program till acceptable results are obtained or till some pre-set limit of time. It will be difficult, however, to include criteria or rules that are yet unknown but may become important in the future. The other approach is to utilize an expert system that allows the inclusion of rules in a more flexible form. Since this research is only the first step in the process of achieving automated system identification, it is decided to adopt this more flexible approach. A program available in the public domain for expert systems is utilized (Giarratano and Riley, 1989). Using this program, the only thing needed for implementation is to write a set of rules in the language of the program. These rules at the present time include (1) bounds of damping ratio, (2) acceptable errors of matching for different time windows, (3) bounds of ratio of higher mode frequency to the first frequency, and (4) adding number of modes included in the identification process, etc. In the current design, the identification process is carried out for the longitudinal direction of the building first in a single input-multiple output setup using only longitudinal motions. The identification for the transverse and torsional modes of vibration is then carried out using transverse motions. This implies the independence of the longitudinal response from the transverse response. Based on experience from analyzing building records of past earthquakes, this assumption does not pose any real difficulty in modeling the actual behavior of a building as long as the building is regular in geometry and stiffness.

This automated system identification processor has been tested against the records of two buildings. One is a four-story steel frame building with records available at the ground, the second, and the roof levels. The Loma Prieta Earthquake record of this building was analyzed. The record was 30 seconds long. In the pre-processor, it was specified that each time window be three seconds long. The automated identification process for all ten windows of the longitudinal and transverse responses took about twenty minutes in a 100 MHz Pentium processor PC. The initial guess of the frequencies was arbitrarily chosen as 1 Hz for the first longitudinal, transverse, and torsional modes. The results obtained were the same as those from previous studies using the same identification method but with extensive human intervention in repeated trial-and-error runs. Same can be said about the case of the seven-story RC building damaged in the Northridge Earthquake. Since more accelerometer data were available than the four-story steel frame building, the system identification took fifty minutes. The longer time was also due in part to the highly nonlinear nature of the response. As a rule of thumb, the longer it takes to identify the parameters, the larger the change of parameters from window to window. The same record of the building took several days of trial-and-error previously to obtain acceptable identification results.

AUTOMATED SAFETY EVALUATION

Safety evaluation of buildings is a very difficult subject even with on site inspection by experienced engineers. The difficulty is compounded by the fact that not all signs of damage are visible and not all visible signs of damage reflect structural damage. Without the benefit of on site inspection, the safety evaluation using only recorded data can only be tentative at best. Thus, the goal of automated safety

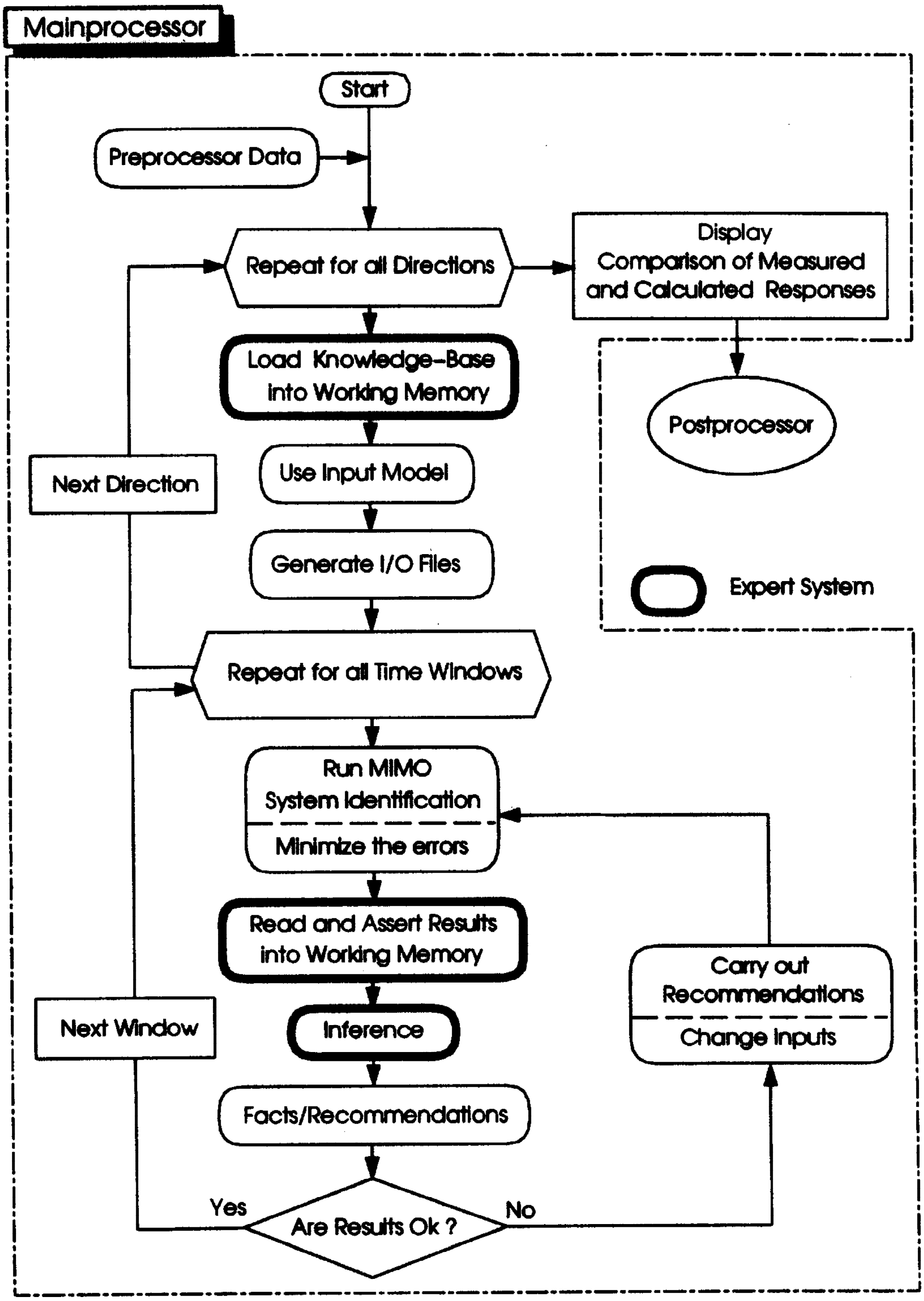

Fig. 1. Flow diagram of the main-processor executing system identification

evaluation must be set at only providing the owner of the building with some guidance for action, not any definitive conclusion on damage. Nonetheless, much can be done to make the automated process as useful as possible.

There are several points need to be made about safety evaluation or damage assessment. In studying buildings damaged by past earthquakes and reports of damage from laboratory tests (Algan, 1982), it is apparent that damage assessment can only be conducted on a case-by-case basis. Not only buildings of different types cannot be assessed using the same set of criteria but buildings of the same type must be viewed individually because of the difference in design, effects of nonstructural elements, soil-structure interaction, etc. Furthermore, not a single damage index can be considered to have an exclusive claim on the damage state. Then, there also is the description of damage itself, which remains to be non-precise, non-quantifiable.

In this study, four states of damage are used to describe the extent of damage: no damage, slight damage, moderate damage, and severe damage. As the language on damage must be fuzzy, so is the degree of confidence in assessing the damage. Thus, four states of probability are used: unlikely, not likely, likely, and very likely. All these are in keeping with the theory of fuzzy logic and its application to damage assessment (Yao, 1985).

The criteria used for damage assessment depend on what can be obtained from the system identification and the analysis of recorded data. For example, with the introduction of a mode-shape interpolation scheme, story drift, shear force, and overturning moment can be calculated at every story of the building (Mau and Aruna, 1994). For the present study, it was decided to include only the following five items: maximum story drift ratio, change of fundamental frequency, absolute value of fundamental frequency, permanent story drift, and abnormal signals. Numerical value of the first three items can be obtained from system identification. The last two can be assessed by analyzing the uncorrected data. Each of these five items must be compared with a given set of criteria which are linked to a state of damage. Only the framework of the damage assessment is setup in this study. For a particular building, it remains to be the responsibility of an expert to specify this linkage. An example of the linkage would be: IF the maximum ground story drift ratio of this building is less than 0.5%, THEN it is very likely that building has no damage. The expert has the choice of the quantity of 0.5%, the statement of probability as unlikely and the statement of damage state as no damage. Another example would be: IF the change of fundamental frequency during the earthquake is greater than 50% but less than 70%, THEN it is likely that the building is moderately damaged. Thus, each item may be linked to a statement on damage. Furthermore, the concurrence of more than one criteria must be dealt with as it is often the case. Intuitively, the concurrence of large frequency change, large story drift and abnormal signals should make a more compelling case of some degree of damage than the occurrence of a single criterion being met. An automatic combinational rule for such concurrent situation is being developed using fuzzy logic. The users, however, may choose to override the default logic and supply one of their own.

CONCLUDING REMARKS

This study provides a promising first step in the development of a quick response methodology for post-earthquake safety evaluation of buildings equipped with a PC-based seismic recording system. A fully automated program has been completed, although its application is for the time being limited only to regular buildings with a standard accelerometer deployment. The damage assessment logic utilized is primitive but easy to implement by an expert in structural engineering.

An area for future improvement is to include more sophisticated rules in the expert system for automated system identification so that the program can be used for any building with any kind of accelerometer deployment. On the other hand, it is not difficult to modify the program to make it easier to be fine tuned for application to a particular building. Using past earthquake response data of the building, for example, it should be possible to set up the system identification algorithm for future earthquakes in such a way that the system identification process is guaranteed to complete in success in a very short period of time of, say, a few minutes.

The automated safety evaluation process itself is fast as long as computer time is concerned. The difficulty is in the choice of criteria. Again, information from past earthquake is of vital importance. At the least, results of data analysis of past records that correspond to no structural damage of the building can be used to provide a bound within which a state of no damage can be proclaimed with confidence. Thus, the automated program should be viewed as one that needs continuous updating. Such updating can be made automatic by the employment of expert system again.

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