Code Development for Nonstructural Components

by Tsu T. Soong

Abstract

The importance of nonstructural component issues in seismic design and performance evaluation is now well recognized. Today, major building codes and seismic design guidelines exist which address seismic design forces for various nonstructural components In these provisions, the design force is formulated as an equivalent static lateral force applied to the approximate center of gravity of the component being considered. While simple formulas are necessary for the sake of design applications, they contain a certain amount of arbitrariness and subjectivity which produce ambiguous results and inconsistent design forces among different codes and provisions. Furthermore, they do not reflect the level of understanding of the behavior of nonstructural components that has been achieved through theoretical analyses, experiments, and observation data from past earthquakes.

A major thrust of NCEER s work in this area has been to critically assess current design force formulas for nonstructural components as they exist in the 1991 NEHRP provisions, to identify their shortcomings, and to recommend revisions which would bring them more in line with current state-of-the-knowledge in this area. These revisions were recommended within the framework of the equivalent lateral force format for practical applicability

Another major activity in this area has been concerned with the development of system-based design provisions for nonstructural components. Research activities in risk analysis of nonstructural components have led to a new classification scheme for components which are susceptible to earthquake-induced vibratory effects and critical enough to require special consideration. Since component damage may be less critical than overall system functionality, classification based on the seismic fragility of systems of nonstructural components have also been given priority for the development of design and performance analysis procedures.

Collaboration

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Objectives and Approach

The objective of this research is to improve existing code provisions and develop more rational model codes for nonstructural components and systems through analyses, experiments, and experience data.

The approach to this research was to assess current design formulas for nonstructural components as they exist in current code provisions and recommend revisions, obtained through analytical and experimental research and the use of experience data obtained from past earthquakes. The project also worked toward developing system-based model codes based on the seismic fragility of critical systems of nonstructural components.

This research task is part of NCEER's Nonstructural Components Project. Task numbers are 90-2002, 91-3212, 92-3201, 93-3202, and 93-4201.

Accomplishments

Code Update Effort

A major effort on the part of NCEER's investigators in the Nonstructural Components project was devoted to the 1994 update to the 1991 National Earthquake Hazards Reduction Program (NEHRP) provisions for nonstructural components (architectural, mechanical and electrical components and systems). The major activities included.

■ A critical assessment of current seismic design formulas for nonstructural components, identification of some of their shortcomings, and recommended revisions.

■ Sponsorship of a 1994 NEHRP Update Workshop, where participants included experts in the field and selected members of the Task Subcommittee 8 (TS8) of the Building Seismic Safety Council. TS8 was responsible for this update effort. The objective was to reach a consensus on the revised force and displacement formulas.

In the first area, the major thrust was to correct deficiencies and inconsistencies in the current design force formulas for nonstructural components and to recommend revisions which would bring them more in line with current state-of-the-knowledge in this area.

Three options were recommended which depended upon different levels of consideration of structural and component effects (Soong et al., 1993) Each option preserves the equivalent lateral force concept, a static procedure which can be justified based on dynamic analysis, experimental evidence, and observation data from past earthquakes. Special attention was paid to soil type effect, location effect, structural period effect, structural yielding effect, and anchorage detail effect. Through case studies, they were shown to represent a significant improvement over the 1991 NEHRP design force formulas.

Current provisions do not include design guidelines based on displacements or deformations on the part of nonstructural components under seismic excitations. Since excessive movements are causes of a significant number of past nonstructural failures, simple displacement equations were also proposed which can be used to estimate flexible support deformation and the amount of sliding a nonstructural component can experience during a seismic event

These revisions, together with other proposals, were presented at the NCEER-sponsored 1994 NEHRP Update Workshop held in January, 1993 in Irvine, California. The following individuals attended the workshop:

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These efforts have helped in the development of a set of proposed seismic force equations that have taken the following into account, some of which were not considered in either 1991 UBC or the 1991 NEHRP Provisions (Bachman and Drake, 1994):

- component weight and mass distribution, including dynamic properties;
- location of structure within regional seismic zone;
- seismic response of the primary supporting structure to earthquake input motions, including site effects;
- location of component within structure;
- the safety hazard which would result should the component separate from structure;
- importance of component function to operation of facility; and
- component anchorage ductility and energy absorption capability.

Additional desired attributes of the proposed force equations include:

- input accelerations for components which rationally reflect actual structural accelerations at the component attachment point(s);
- input accelerations for components which are consistent with the input design ground motion at grade level; and
- input acceleration for grade-level components should match grade level design ground motion accelerations used in the design of the structure

In addition to the force equations, displacement input is needed for the seismic design of cladding, stairwells, windows, piping systems, and other systems that are connected to the structural frame at multiple levels. The displacements should rationally reflect the actual structural displacements of the structure at the attachment points.

Neither the 1991 UBC nor the 1991 NEHRP Provisions provide design equations for seismic relative displacements. In this effort, equations were proposed for the 1994 NEHRP which are based on either the building structural analysis or the building drift limitations, each of which is provided for in the structural provisions of the 1991 and 1994 NEHRP Provisions.

Work is continuing on several important code-related issues. These include methods of including the R-factor in the seismic analysis of nonstructural components located in yielding structures and in base-isolated structures. Calibration of 1994 revised force and displacement equations based on the Northridge experience data has also been a focus of NCEER's activities.

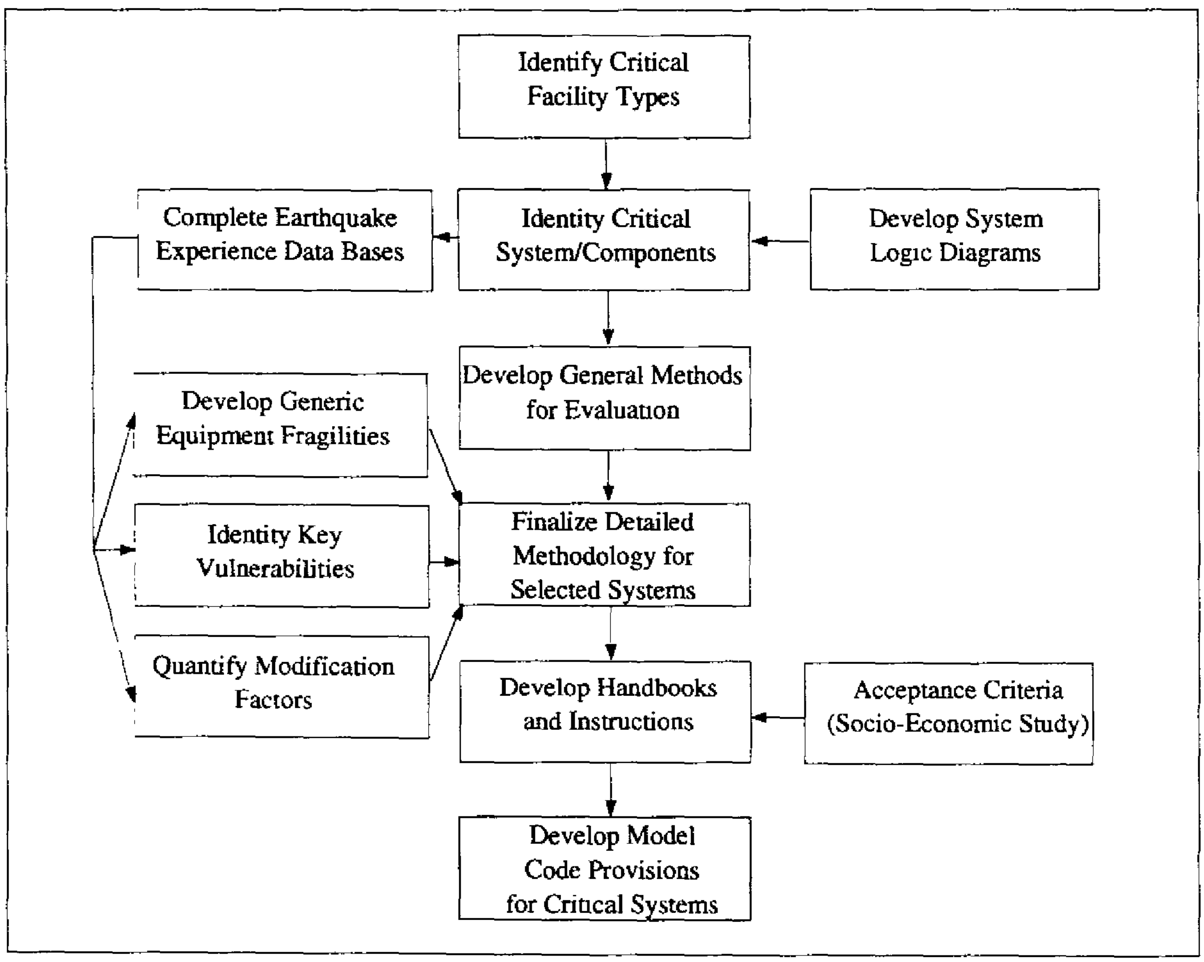
System-based Code Development

The focus of this work was to quantify the reliability of critical nonstructural systems within critical facilities with the goal of obtaining model code provisions (Porter et al., 1993).The seismic reliability of nonstructural systems is a matter of significant economic and life-safety consequence This program has been aimed toward reducing earthquake risk for critical equipment systems and facilities by carrying out multi-phase tasks as shown in figure 1, consisting of the following key steps·

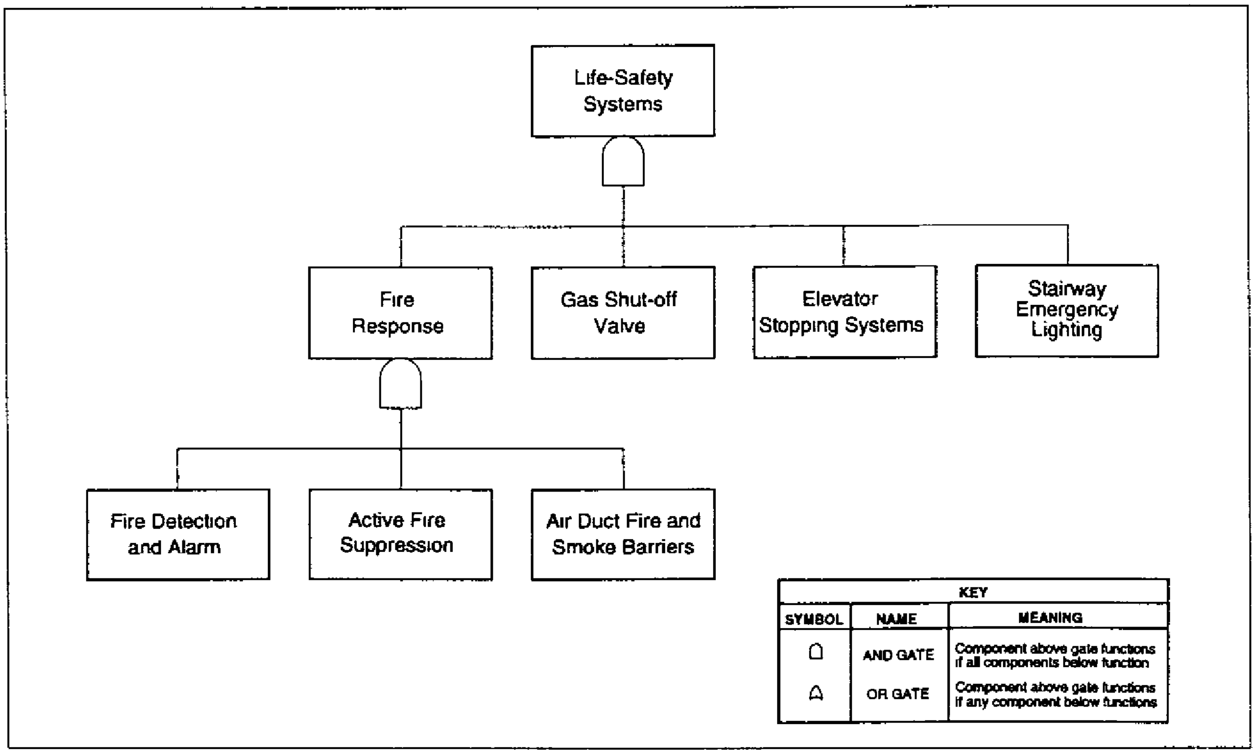
■ Compile data on the morphology and history of equipment systems Examine sample facility types and equipment systems. Incorporate these data into risk tables and equipment performance data bases.

■ Formalize generic fragility assessment procedures (FAPs) to assess fragility of all critical equipment. Apply prototype FAPs to critical equipment data bases.

■ On the basis of prototype FAPs, develop a prototype critical system reliability assessment methodology (CSRAM) for estimating casualties and economic losses due to equipment damage.



■ **Figure 1**
System-based Code Development



■ Figure 2
Data Processing Center Life-Safety System

■ As an example application, assess at a regional level the reliability of all equipment systems affected by selected scenario earthquakes. Estimate the inventory of population at risk, buildings, equipment systems, and equipment components. Develop scenario earthquakes for seismic regions.Apply the prototype CSRAM to inventory estimates. Characterize loss estimates by facility type system, component, etc.

■ Develop guidelines for judging or improving critical equipment reliability. Prepare a user's guide for use by engineers without seismic expertise. Field test user's guide and CSRAM.

■ Perform pilot dissemination of user's guide, providing training in its application.

Generalizations regarding equipment function and seismic reliability have been developed by reviewing the major components, criticality for life-safety and normal operations, and system dependencies of four important facility types: high-rise office buildings, telephone central offices, data processing centers, and hospitals

The use and criticality of facility components and lifeline services are illustrated in logic diagrams such as shown in figure 2 for a data processing center. These diagrams are constructed for each major system at each facility type. The diagrams illustrate system dependencies and redundancies and identify basic components on which each system relies. By following the entire sequence of logic trees, the basic components can be determined and seismic reliability may be discussed and evaluated.

Results of this study demonstrate that equipment attributes leading to poor performance in earthquakes can be identified and avoided and can be eliminated from existing facilities. The study also shows that equipment failures in moderate and large earthquakes are typically dependent on details of construction and equipment configurations; they are typically not a function of ground motion amplitude. Detailed equipment performance data, such as those compiled for this study, can be used to develop empirical criteria for new design. Because equipment performance data demonstrate failure probability of a random sample, these data can also be used to assist in damage prediction models, statistical evaluations, fragility modeling and probabilistic risk assessments.

This study forms much of the basis for answering several important questions on the costs and benefits and improving equipment seismic reliability, the priorities for addressing reliability, and the methods for increasing reliability of new system designs and assessment of existing systems.

Technical References

Bachman, R.E. and Drake, R.M., "1994 NEHRP Provisions for Architectural, Mechanical and Electrical Components," Proceedings, 5th National Conference on Earthquake Engineering, Chicago, 1994.

Chen, Y.Q., and Soong, T.T., "Seismic Response of Secondary Systems," Engineering Structures, Vol. 10, 1988, pp 218-228

Porter, K., Johnson, G S , et al , "Seismic Vulnerability of Equipment in Critical Facilities: Life-Safety and Operational Consequences," Technical Report NCEER-93-0022, National Center for Earthquake Engineering Research, Buffalo, November 24, 1993.

Soong, T T , Chen, G. et al., "Assessment of the 1991 NEHRP Provisions for Nonstructural Components and Recommended Revisions," Technical Report NCEER-93-0003, National Center for Earthquake Engineering Research, Buffalo, March 1, 1993.

Publications

Journal Papers

Chen, Y Q., and Soong, T T , "Seismic Response of Secondary Systems," Engineering Structures, Vol. 10, 1988, pp. 218-228.

Chen, Y Q , and Soong, T.T., "Stochastic Response Sensitivity of Secondary Systems to Primary Structural Uncertainties," Structural Safety, Vol. 6, 1989, pp 311-321

Lai, M.L., and Soong, T.T., "Statistical Energy Analysis of Primary-Secondary Structural Systems," Journal of Engineering Mechanics, ASCE, Vol. 116, No. 11, 1990, pp 2400-2413.

Chen, G , and Soong, T.T., "Power Flow and Energy Balance Between Nonconservatively Coupled Oscillators," ASME Journal of Vibration and Acoustics, Vol 113, No. 4, 1991, pp 448-454.

Lai, M.L., and Soong, T.T., "Seismic Design Considerations for Secondary Structural Systems," ASCE Journal of Structural Engineering, Vol 117, No 2, 1991, pp 459-472.

Chen, G , and Soong, T.T., "Power Flow and Energy in Primary-Secondary Systems," ASCE Journal of Engineering Mechanics, Vol. 118, No. 5, 1992, pp. 1046-1051.

Huang, C.D , Socha, L., and Soong, T T , "Stochastic Sensitivity Analysis of Primary-Secondary Structural Systems," Engineering Structures, Vol. 15, No 2, 1993, pp. 135-142.

Huang, C.D., Zhu, W.Q., and Soong, T.T., "Stochastic Response and Reliability of Secondary Systems Mounted on MDOF Yielding Structures." ASCE Journal of Engineering Mechanics, Vol. 120, No. 1, 1994, pp. 177-196.

Zhu, W.Q., Huang, C.D., and Soong, T.T., "Response and Reliability of Secondary Systems in Yielding Structures," Journal of Probabilistic Engineering Mechanics, Vol. 9, No. 1, 1994, pp. 145-155.

Chen, G., and Soong, T T , "An Energy-based Dynamic Analysis of Secondary Systems," ASCE Journal of Engineering Mechanics, Vol. 120, No. 3, 1994, pp 514-534.

Huang, C.D., and Soong, T T , "Stochastic Sensitivity Analysis of Nonlinear Primary-Secondary Structural Systems," Engineering Structures, Vol. 16, No. 2, 1994, pp. 91-96

NCEER Reports

Manolis, G.D , Juhn, G., and Reinhorn, A.M , "Experimental Investigation of Primary-Secondary System Interaction," Technical Report NCEER-88-0019, National Center for Earthquake Engineering Research, University at Buffalo, May 27, 1988.

Chen, Y.Q., and Soong, T.T., "Seismic Behavior and Response Sensitivity of Secondary Structural Systems," Technical Report NCEER-89-0030, National Center for Earthquake Engineering Research, University at Buffalo, October 23, 1989.

Ibrahim, Y., Grigoriu, M., and Soong, T.T., "Random Vibration and Reliability Analysis of Primary-Secondary Structural Systems," Technical Report NCEER-89-0031, National Center for Earthquake Engineering Research, University at Buffalo, November 10, 1989.

Chen, D.C.K., and Lutes, L.D., "Nonnormal Secondary Response Due to Yielding in a Primary Structure," Technical Report NCEER-90-0002, National Center for Earthquake Engineering Research, University at Buffalo, February 28, 1990.

Soong, T.T., Chen, G., Wu, Z., Zhang, R-H., and Grigoriu, M., "Assessment of 1991 NEHRP Provisions for Nonstructural Components and Recommended Revisions," Technical Report NCEER-93-0003, National Center for Earthquake Engineering Research, University at Buffalo, March 1, 1993.

Singh, M.P., Suarez, L.E., Matheu, E.E., and Maldonado, G.O., "Simplified Procedures for Seismic Design of Nonstructural Components and Assessment of Current Code Provisions," Technical Report NCEER-93-0013, National Center for Earthquake Engineering Research, University at Buffalo, August 4, 1993

Chen, G., and Soong, T.T., "An Energy Approach to Seismic Analysis and Design of Secondary Systems," Technical Report NCEER-93-0014, National Center for Earthquake Engineering Research, University at Buffalo, August 6, 1993.

Porter, K., Johnson, G.S., Zadeh, M.M., Scawthorn, C., and Eder, S., "Seismic Vulnerability of Equipment in Critical Facilities: Life-Safety and Operational Consequences," Technical Report NCEER-93-0022, National Center for Earthquake Engineering Research, University at Buffalo, November 24, 1993.

Lifelines and Highways

Damage sustained by lifelines and highways in recent earthquakes and the multi-million dollar losses that result from service disruption, have reinforced the need to perform comprehensive studies on these elements of the built environment. Frequently taken for granted, lifelines include water, gas, oil, electricity, transportation and telecommunication systems. Motivated by the damaging potential of fire following an earthquake, the Center's Lifeline Project began by performing detailed studies of the water supply systems in San Francisco and Memphis. These studies were later expanded to oil and gas transmission lines in the Central United States and more recently to electricity supply systems. Geotechnical studies have focused on liquefaction and other sources of large ground deformation which have serious consequences for buried lifelines. Systems modelling, fragility assessments, the economic impacts of service disruption and the societal consequences of releases of hazardous or toxic materials have also been studied. Transportation systems are major lifelines and the Center's Highway Project focuses on the seismic vulnerability of both existing and future highway construction. All components of the highway system are being studied including short and long span bridges. The research areas include defining the seismic and geotechnical hazard, developing conventional and innovative retrofit methods by using smart materials and protective systems, applying risk assessment methodologies to highway networks, defining importance and performance criteria, improving prioritization algorithms, and estimating the highway stock. The development of manuals for the evaluation and retrofit of existing lifelines and the preparation of performance-based standards for all new lifelines are long term goals.