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THE FEMA-USC HOSPITAL PROJECT: NONSTRUCTURAL MITIGATION IN HOSPITALS

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SUMMARY

In the 1994 Northridge Earthquake, 68 Hospitals in the region had their normal operations disrupted by nonstructural damage. This experience provided further evidence that the functionality of a hospital during the critical hours following an earthquake depends largely on control of damage to nonstructural elements, equipment, and contents. Recent passage and enforcement of California SB1953, which requires seismic upgrading of hospitals and critical care facilities, has a major focus on nonstructural damage control.

In 1997, FEMA funded a major multi-year study entitled "Development, Evaluation, and Implementation of Standards for Seismic Mitigation Measures for Nonstructural Components in Hospitals and Critical Care Facilities." Centered at the University of Southern California, this study was a collaboration of academic researchers, industry experts, and regulatory agencies. An integrated study plan combined the efforts of members of the USC Schools of Engineering, Medicine and Public Administration, the USC Institute of Safety and Systems Management, private engineering firms, and the California Office of Statewide Health Planning and Development (OSHPD). The team evaluated the performance of, assessed the impact on hospital function of, and developed effective seismic mitigation measures for nonstructural elements, equipment, and contents. A "systems" approach was followed, wherein the performance of hospital systems, not just individual components, was rigorously studied.

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Study results are disseminated through a series of project reports. Through collaboration with regulatory bodies and committees, specific results of the study are being used to modify and augment current seismic regulations. This paper presents a brief overview of this project.

INTRODUCTION

In a severe earthquake event, acute care hospitals and facilities must provide the critically injured and otherwise traumatized with immediate medical attention and necessary care. For the hospitals and facilities to remain functional for this purpose, not only must their building structures remain safe for continued occupancy, but their nonstructural components must remain functional as well. These nonstructural components include elevators, stairs, HVAC systems, sprinklers and other fire suppression systems, communications and utility systems, as well as a variety of medical equipment for life support, laboratory test, operation and other primary and secondary needs for patient care.

The present study developed the major elements of a seismic code framework to guide the implementation of cost-effective standards of practice to ensure that the nonstructural components within acute care hospitals and facilities are effectively seismic resistant. In this effort, the particular importance of each component in effecting the seismic fragility was identified from the systems point of view. Each component was then categorized with respect to its importance and recommendations were made to improve its seismic resistance.

The overall organizational chart for the major elements of the project is shown in Fig. 1, where it is seen that there are three broad categories of tasks: Medical, Engineering, and Socio-Economic tasks, with the "output" of the various tasks feeding directly into recommendations for new nonstructural mitigation methods, codes and regulations.

In this paper, the authors provide a brief summary of some of the major tasks and results of the FEMA-USC Hospital project, which focused on the optimization of the performance of important hospital nonstructural components, through the application of an integrated approach for performing seismic risk assessment.

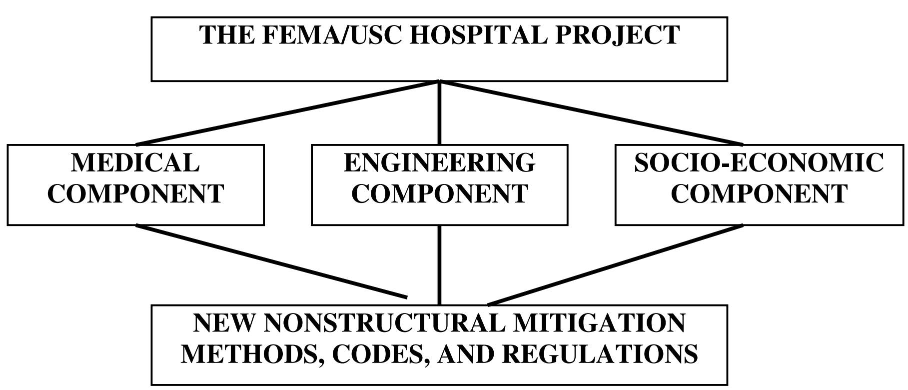


Figure 1: Major FEMA-USC Hospital project components.

SEISMIC RISK ASSESSMENT

Tools for Optimizing Seismic Risk Analysis of Nonstructural Components in Hospitals

Critical facilities, such as hospitals, are required to maintain certain functions during and after a seismic event. A healthcare center, in order to be functional after an earthquake, should have a high seismic reliability. There are several approaches for each facility to increase its reliability. Selecting the optimum strategy to maximize the reliability of hospital performance under extreme events, while minimizing the attendant cost, is a time-consuming and challenging task. To address this issue, collections of software tools, based on probabilistic seismic risk assessment methods for nuclear power plants (Ravindra [1]), were developed, in order to provide tools for decision makers involved with the healthcare industry.

Decision makers can use these tools to quantify the risk exposure and define criteria for optimum allocation of mitigation resources. As an illustration, consider the following example. Assume that it is required that a piping system within a hospital stays functional after a seismic event, and that the piping system is depended only on two subcomponents: a water tank and a single pipe. There are several possible choices to improve the system's seismic reliability within the bounds of a fixed retrofitting budget. Two of the choices could be either adding an additional system (a second water tank and another pipe), or strengthening the connections of the existing water tank and using a stronger pipe. Which will be the best solution for such a simple system? Determining the optimum decision even for such a simple system is not that simple. The management team in charge of the decision can use the tools under discussion to define both scenarios, and to determine which one is the optimum solution with the highest reliability and the lowest cost.

The methodology requires several inputs and data: (1) the system fault tree, (2) the components fragility data, and (3) information concerning the site hazard analysis. The analysis tools can assist technical and non-technical members of the management team to: sketch the system fault tree in a graphical environment; use the database of critical hospital equipments fragility data; estimate the fragility data of hospital equipments with the ready-made calculation sheets; access the geographical location of all major health care facilities and all major earthquakes in the state of California for hazard analysis; and minimize their cost (objective) function. The cost function to be minimized can be a weighted combination of several factors such as budget, component cost, environmental issues, social effects, or other factors that decision-makers might wish to include in their decision process.

Figure 2 shows a graphical depiction of the major components involved in implementing the methodology under discussion.

Methodology and Tools

The methodology is based on the seismic risk analysis of nonstructural components in hospitals, in order to maximize the overall system-level reliability by minimizing the objective function. The tools were developed or adopted in order to simplify the implementation of the seismic risk assessment, and to expedite the decision-making process. Each of the major parts of the methodology, and the corresponding tools are described and discussed below.

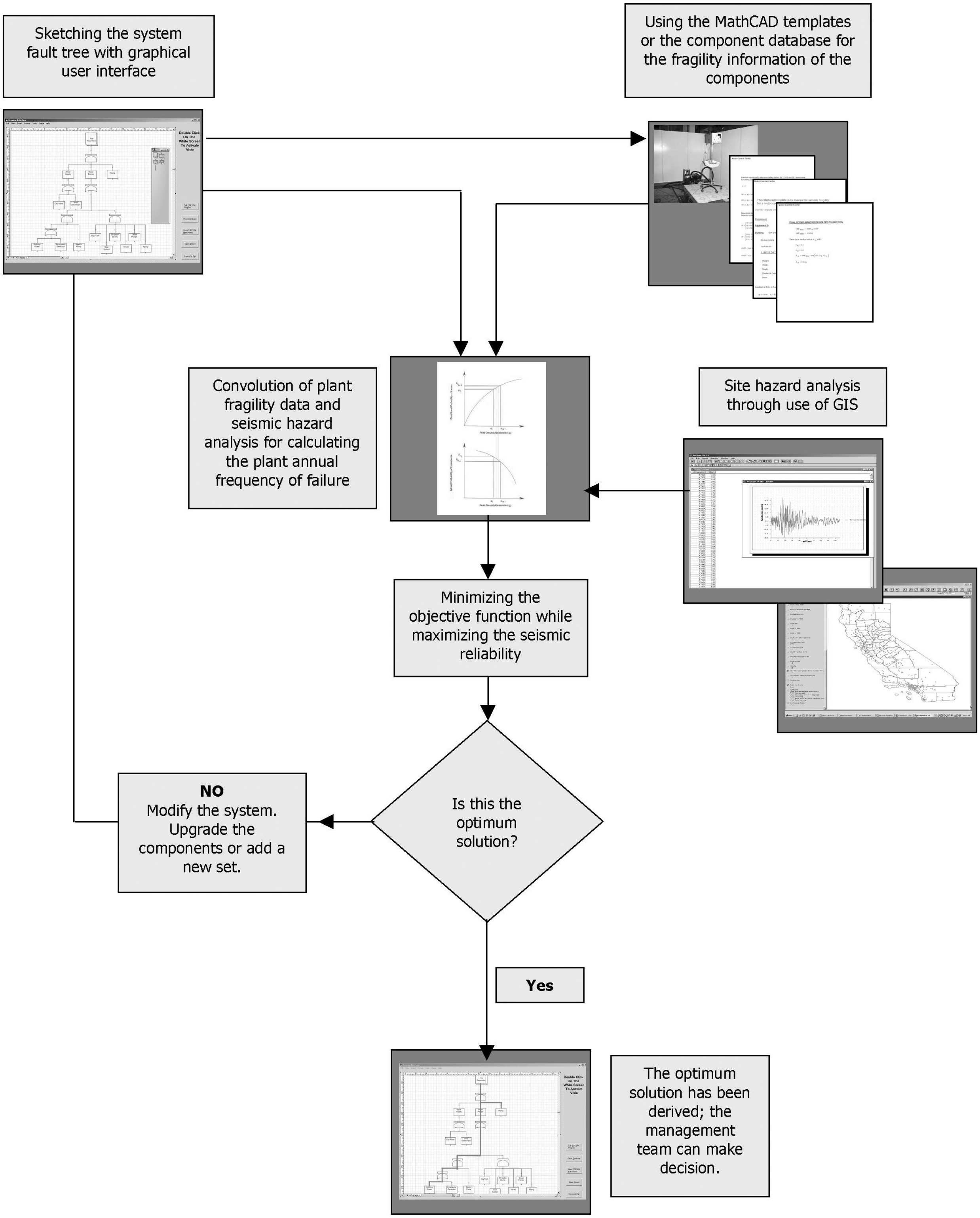
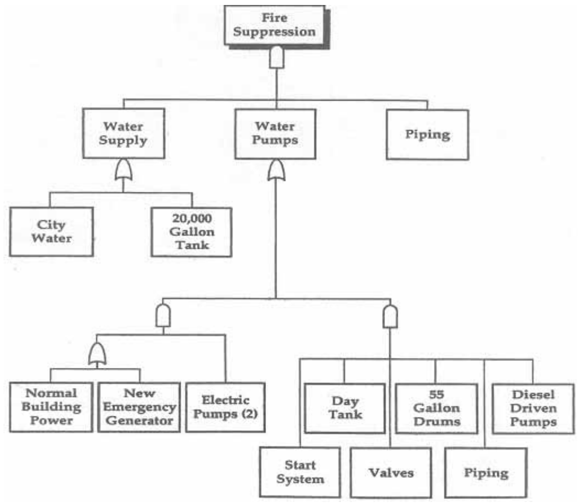
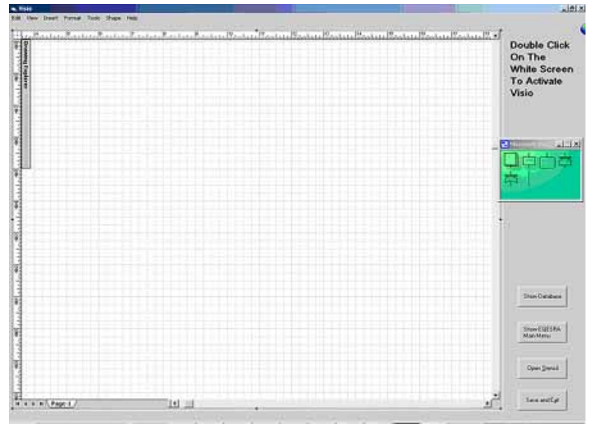


Figure 2: An overview of the methodology and screen shots of the methodology components. The user can use the GUI to sketch the system fault tree, use the hospital equipment database or the calculation sheets to estimate the components fragility data, and use the GIS based tool to evaluate site hazard curves in order to optimize the cost-saving function with the highest possible seismic reliability.



(a)



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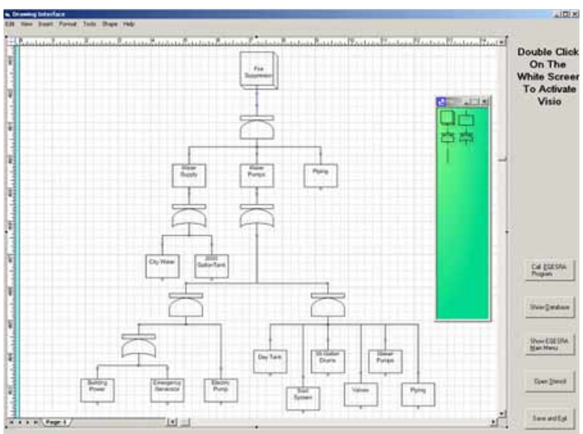


(c)

Figure 3: (a) San Francisco High-Rise Fire Suppression System (Grigoriu [12]); (b) The GUI screen shot; (c) The San Francisco High-Rise Fire Suppression System sketched in the GUI.

System Fault Tree

The system fault/event tree is the most important step that describes the logical dependencies between the system and its subcomponents (Hoyland [2]). The fault tree should consist of all the components and subsystems on which the system functionality depends. The fault tree is defined through Boolean algebra with logical gates (Benjamin [3], and Ang [4]). It requires that the technical staff of the management team to derive the proper fault tree for the system. For healthcare facilities, the FEMA-USC Hospital project team conducted a thorough study to classify and prioritize essential systems in hospitals under extreme events, (Myrtle [5]). Such information can be utilized in the derivation and construction of appropriate fault trees.

A user friendly, Graphical User Interface (GUI) was developed to simplify the procedures of deriving the fault tree (Fig. 3). The user can sketch the system and its components, then assign the desired logical gates to define the system's fault tree. The GUI will generate the corresponding Boolean equation. This Boolean equation will then be used as input for the seismic risk assessment tool.

Components Seismic Fragility Curves

The components fragility is the failure rate defined as a function of a ground-motion parameter, like peak ground acceleration (PGA) (Kennedy [6]). The components fragility is assumed to be a two-parameter lognormal distribution function with median A_m and (total) log-standard deviation β_C (Shinozuka [7]):

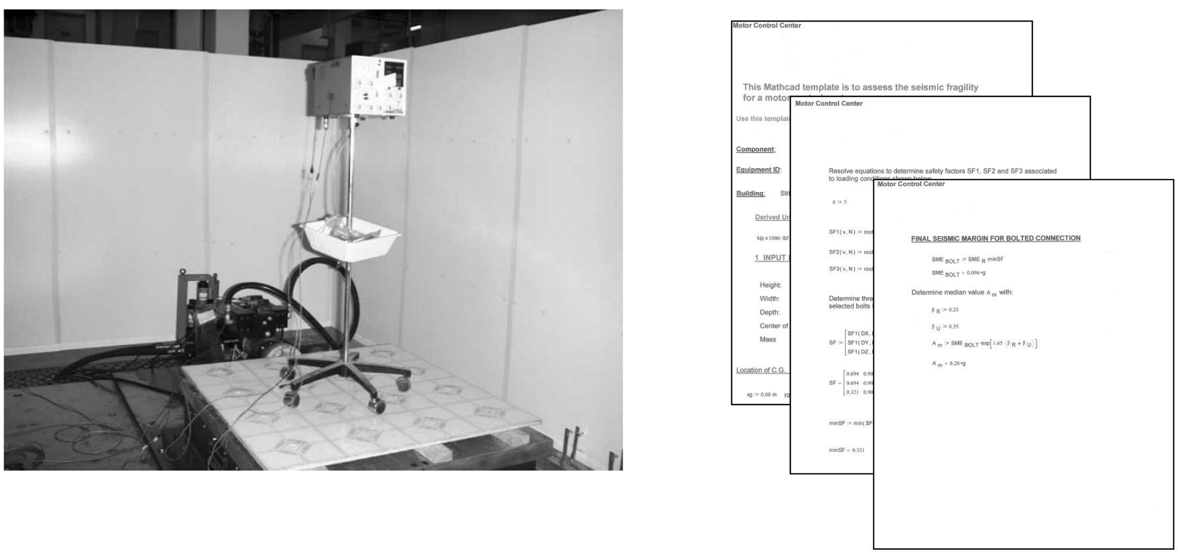
$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2} \qquad \text{(Eq.1)}$$

Where β_R and β_U represent randomness and uncertainty components of the lognormal standard deviation of support motion. The component fragility function is then given by:

$$F_x(\alpha) = \Phi[\frac{\ln(\alpha / A_m)}{\beta_C}] \qquad \text{(Eq.2)}$$

Where $\Phi(.)$ is the standardized normal distribution function, and α is the ground-motion parameter. There are two approaches for calculating the fragility parameters: (1) Empirical, and (2) Analytical. The empirical approach is based on the failure rate of the equipment during evaluation tests, while the theoretical approach is based on the statistical methods and nonlinear dynamic analysis (Shinozuka [8]).

A database of various pieces hospital equipment -- those critical to the functioning of a hospital following an earthquake -- was created by interviewing the hospital personnel that experienced the 1994 Northridge earthquake. A series of experimental tests were also performed on representative medical equipment (Fig. 4a), and sets of MathCAD calculation sheets (Fig. 4b) of theoretical approaches were prepared for some of the equipment. The user can enter the fragility data of components through the GUI to generate the proper format for the risk assessment tool.



(a) (b)

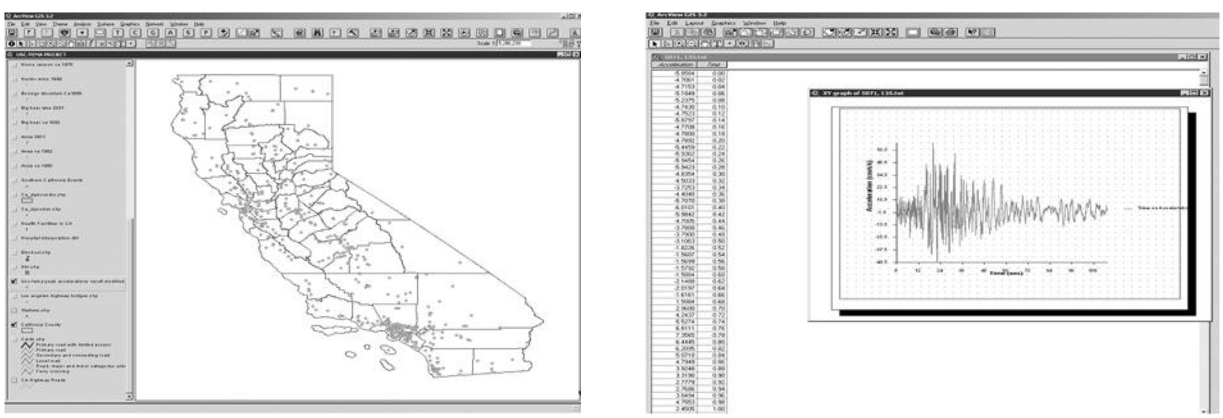
Figure 4: (a) Experimental tests for estimating fragility data of a sample medical equipment stand mounted on the USC seismic shaker; (b) Samples of MathCAD calculations sheets for calculating component fragility data.

Site Hazard Analysis
This is characterized by the annual frequency of exceedance of one of the ground-motion parameters of all possible earthquakes in the vicinity of the site. It was customary to calculate the annual frequency of peak ground acceleration (PGA); however, recently the preferred parameter is the response spectra acceleration (SA). For risk assessment purposes, there should be consistency between the ground-motion parameter chosen for the component fragility probability and the site hazard analysis.

Following are the main steps for calculating the site hazard analysis (Ravindra [1], Beltrán [9]):

1. Identifying all the seismic sources, such as fault or tectonic plates.
2. Earthquake history of the region.
3. Attenuation laws to estimate the earthquake induced motion at the site
4. Representation of the calculations in probabilistic format.

The hazard analysis is based on various probabilistic parameters. To include the probabilistic nature of the parameters within the hazard analysis, a family of hazard curves is estimated at the site. The site hazard analysis is a complicated and time-consuming calculation that depends on the geology, topography, and the seismic data of the site and region. A tool based on Geographic Information Systems (GIS) has been developed which will help seismologists to conveniently access needed seismic data for the site hazard analysis. This tool has databases of the geological information for major healthcare facilities and major earthquakes within the state of California (Fig. 5). The user can define the attenuation laws with minor modifications and scripting. The earthquake database can be updated in real-time. The tool is capable of being programmed to automatically access the Internet and download the latest seismic activities. This tool has been designed to assist the technical staff of healthcare facilities in estimating the hazard level of a hospital site in the state of California.



(a) (b)

Figure 5: (a) The health care facilities location and recent earthquake data within the state of California; (b) The earthquake time-history database has been updated through accessing the Internet.

Seismic Risk Analysis
The seismic risk assessment is calculated through the convolution of plant level fragility and site seismic hazard analysis based on the discrete probability calculation methods described by Kaplan [10], and Kaplan and Lin [11]. The plant level fragility is calculated by combining the component fragility levels based on the logical relation defined by the system fault tree (Grigoriu [12]). The convolution operation that calculates the annual frequency of failure is then given by:

$$P_f = -\int_0^{\infty} P_{f|A} \frac{dH}{dA} dA \tag{Eq.3}$$

Where: A : Desired ground-motion parameter.

$P_{f|A}$: Conditional Probability of the plant level failure rate.

H : Probability of the ground-motion parameter being less or equal than A.

The tool developed for the seismic risk assessment reads the system fault tree Boolean equation, the components' fragility data, the site seismic hazard curves, and then calculates the corresponding annual frequency of failure.

Optimization

The optimization scheme is based on the minimization of a cost function in order to gain the maximum achievable seismic reliability for the plant. The cost function is expressed as a linear combination of weighted parameters defined by the user. The parameters can be any suitable measure to be factored in the decision process (e.g., the facility retrofit budget, social-economical effects, environmental issues, and more, which can be unique for each health care facility). The optimization tool that was developed implements a computationally efficient constrained nonlinear optimization algorithm. It uses the output of the seismic risk assessment as the user-defined objective function value to minimize.

Figure 6 shows the major components of the action chart corresponding to the implementation of the various tasks involved in determining an acceptable level of "hardening" for a typical facility.

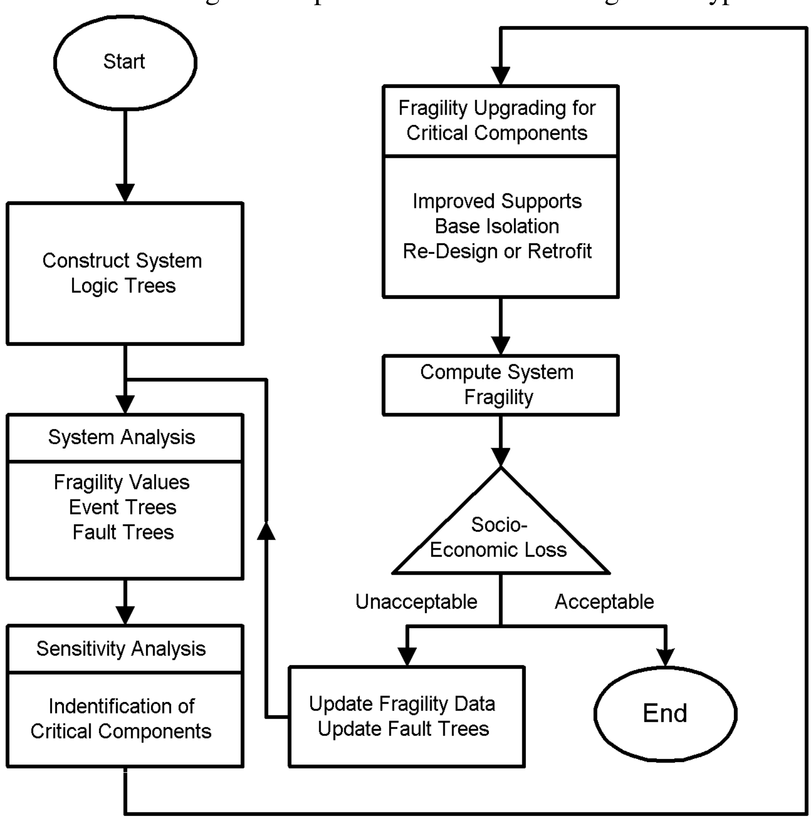


Figure 6: System analysis action flow chart.

EXPERIMENTAL PHASE

The FEMA-USC Hospital project involved the testing of a large collection of representative hospital medical equipment and related nonstructural components. The following sections provide an overview of some of the experimental studies related to an important class of nonstructural components: piping systems, both at the element and sub-component level.

The experimental aspect of the hospital piping study consisted of two phases. In the first phase, an in-depth study was performed on typical 2” and 4” pipe joints, such as threaded couplers, rigid and flexible groove type joints, and compression joints. In the second phase, full-scale piping systems were subjected to dynamic earthquake loads.

To perform the pipe component tests, a custom test apparatus was constructed as shown in Figure 7. The test apparatus consisted of a large steel welded table weighing about 10,000 lb, a computer controlled hydraulic actuator with a capacity of 20,000 lb and 10 inches of stroke, and a custom mounting “boundary element” designed to hold the pipe end rigidly without imposing any stress concentrations, which could cause erroneous results. The computer was programmed using the LabVIEW software to perform three separate types of tests, namely, (1) the ATC 24, (2) the NEHRP, and (3) the ASME fatigue test. The ATC 24 test was of particular interest because of its importance in developing new hospital piping standards for the state of California.

The implementation of the ATC 24 test consisted of first performing a uniaxial load-deflection test to determine the yield load of the pipe/connection. After determining the yield load for a representative sample of the pipe/connection to be tested, a cyclic load test was performed on several virgin test articles. The cyclic test consisted of four full cycles at 25% of the yield load, then 50%, and finally 75%. After completion of the last 75% load cycle, the computer switched to a displacement control and performed four cycles at 100% of yield displacement, then 125%, 150%, etc, until failure occurred. Failure is defined to be when the pipe or connection, which was pressurized to 100 PSI, developed a leak. The applied load and resulting deflection were recorded during the entire test, using the LabVIEW software.

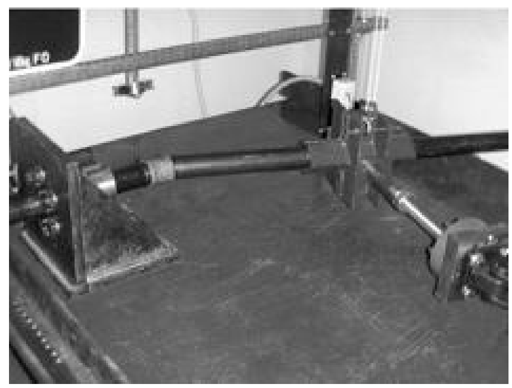


Figure7: Pipe component test apparatus.

The results and subsequent data processing is shown in Figure 8 for a typical 2” flexible groove type connection. Figure 8a shows the load deflection of all the cycles until failure. Two observations can be seen: (1) the load-deflection pattern is not symmetric; that is, the connection appears to be taking more load in compression, and (2) there is a substantial dead-zone in the load carrying capacity of the connection. The asymmetry is due to the fact that the test apparatus had a bias due the geometry of the actuator mounting. The effect of this bias is corrected in subsequent data processing. The dead-zone is realistic, and is characteristic of groove-type connections. This dead-zone can be advantageous if used in a properly designed installation.

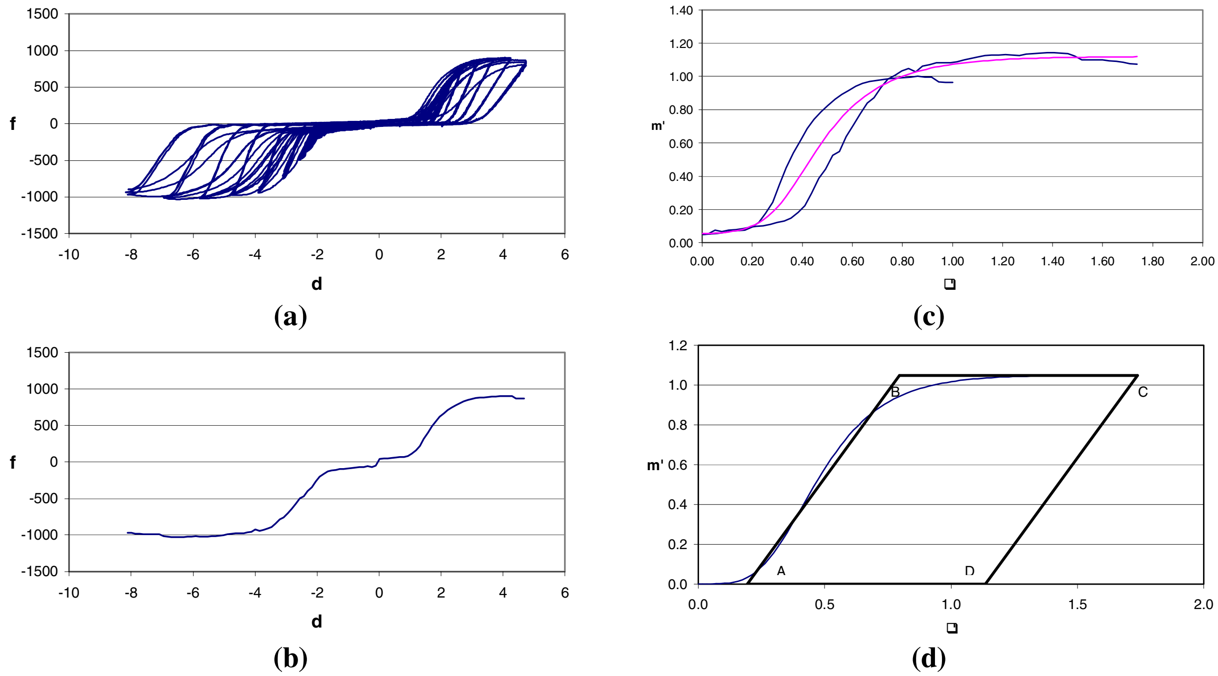


Figure 8: Sample pipe connector test and analysis results; (a) load-deformation of a "groove"-type joint; (b) enveloping backbone curve; (c) analytical fit of the load deflection curves in the positive quadrant; (d) identified, normalized hysteresis loop.

The first step of data processing is to develop an enveloping backbone curve as shown in figure 8b. The next step is to remove the geometric bias from the curve backbone and then take the absolute value of the recorded deflections and force to produce two load deflection curves in the positive quadrant as shown in Figure 8c.

The next step is to curve fit the modified data with a five-parameter sigmoidal function given by

$$Y = t_1 + \frac{t_2}{\left(1 + exp\left(\frac{-x + t_3}{t_4}\right)\right)^{t_5}} \qquad \text{(Eq.4)}$$

Where: x : Modified values of displacement.

Y : Modified values of force.

t_1, t_2, t_3, t_4, t_5 : Five-parameter functions defining the sigmoidal function.

The values of the five parameters are determined using a nonlinear curve fitting routine. The resulting curve fit is also shown in Figure 8c.

The next step is to determine the two "knees" of the sigmoidal curve fit. The knee is defined to be when the slope of the sigmoid curve is equal to one, and is obtained by solving for x in Eq.5:

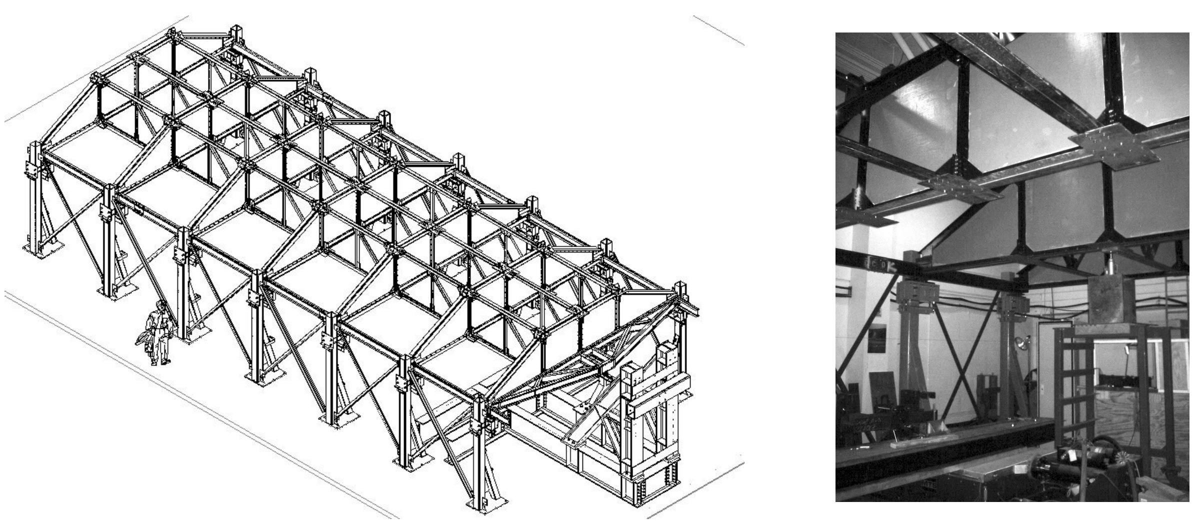
$$\frac{t_2 \cdot \frac{t_5}{t_4} \cdot exp\left(\frac{-x+t_3}{t_4}\right)}{\left(1+exp\left(\frac{-x+t_3}{t_4}\right)\right)^{(t_5+1)}} = 1 \qquad \text{(Eq.5)}$$

There will be, in general, two knee points for the curve fit, provided that the joint under test has a dead zone. Using these two knee points, a straight line going through the points is constructed as shown in Figure 8d and is referred to as the linear load curve.

Next, a horizontal line is constructed that has the same force value as the maximum force observed in the backbone curves. This horizontal curve extends out to the highest displacement value seen during the test. Next, a line is generated from the end of the previous horizontal line down to the abscissa with a slope equal to the linear load line. Finally, a line is constructed from the end of the sloped return curve to the intersection of the original linear load curve and the abscissa. The resulting hysteresis curve is shown in Figure 8d. It is from this hysteresis curve that all of the joint properties (such as ductility, dead zone displacement, and energy dissipation) are derived.

The data processing outlined above has been applied to numerous tests and the results are currently being evaluated for building code implications and system level analytical modeling. While the component level test described previously focused on a single joint at a time, a parallel effort has been underway to construct and test a full-size ceiling complete with a functional piping system. A solid model of the ceiling test is shown in Figure 9.

The size of the ceiling test apparatus is approximately 1000 square feet, and is supported using large linear bearings. The structure is driven with a 50,000 lb hydraulic actuator having a stroke of 10 inches. The large size was needed to represent the size of a typical hospital room with an overhead piping system. The first sequences of tests were conducted in the Spring of 2004.



(a) **(b)**

Figure 9: (a) Solid model of the ceiling test apparatus (notice scale of human operator); (b) a photograph of assembled trusses.

CONCLUSIONS

An integrated study plan combining the efforts of members of the USC Schools of Engineering, Medicine and Public Policy and Planning, the USC Institute of Safety and Systems Management, private engineering firms, and the California Office of Statewide Health Planning and Development (OSHPD) has evaluated the performance of, assessed the impact on hospital function of, and developed a methodology for evaluation of seismic mitigation measures for nonstructural elements, equipment, and other hospital contents. Results were disseminated through project reports, and are being used as technical bases to recommend modification of seismic regulations for nonstructural components.

ACKNOWLEDGMENTS

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