Real-Time Post-Earthquake Performance Evaluation and Damage Detection for Buildings

F. Naeim
John A. Martin & Associates, Inc., Los Angeles, CA, USA

SUMMARY:
Real-time structural health monitoring is not a promise. It is an existing technology that has been deployed and advanced successfully s on many buildings, bridges, and other types of structures. In this chapter we examine the possible advantages as well as implementation schemes for a system which can provide real-time performance and damage information for buildings and other types of structures.

Keywords: buildings, seismic instrumentation, structural health monitoring, performance evaluation, damage detection

1. INTRODUCTION

Immediately following an event that could adversely affect the performance, safety, or operability of a building or a portfolio of buildings, owners and managers of such buildings are in desperate need of reliable information regarding the status of their facilities in order to make rational and justifiable decisions regarding the status and functionality of their facilities. Currently, after extreme events such as an earthquake or a hurricane, building owners and managers need to wait in line for their buildings to be visually inspected and tagged by city officials or evaluated by an engineer in order to assess the status of their building.

While having an engineer in place before an extreme event happens may reduce the wait time for visual inspection and assessment from weeks to days, many buildings need to make a decision within minutes --not days or weeks -- whether their building should remain occupied and operational. Real-time structural health monitoring when combined with state-of-the-art damage detection and performance evaluation methodologies are currently the only method to satisfy that dire need of building owners and managers. Over the past two years, John A. Martin & Associates, Inc. and Digitexx Data Systems collaborated in developing a state-of-the art system for real-time damage detection and performance evaluation (DDPE) resulting in the REFLEXX Smart System for Buildings released in July 2011.

Such a system can provide a substantial and cost-effective incentive for building owners to instrument their buildings and benefit from the status reports that can be generated immediately after any extreme event (earthquake, fire, blast, windstorms, flooding, etc.). With use of some of the techniques implemented in the system even estimates of the cost and time of repairs can be made available to the building owner immediately following a triggering event,

2. REAL-TIME DAMAGE DETECTION AND PERFORMANCE EVALUATION

The current state-of-the-art monitoring systems are based on a highly efficient, multi-threaded software design that allows the system to acquire data from a large number of channels, monitor and condition this data, and distribute it, in real-time, over the Internet to multiple remote locations.

Sensors deployed throughout the building continuously send out data regarding measured accelerations, velocities and displacements from instrumented locations in the structure. If an event such as an earthquake occurs and pre-assigned and changeable thresholds of measurements are exceeded in one or multiple locations, the data (including pre-event memory) and corresponding analyses are automatically saved on a storage device. Once an event is recorded, the system notifies a list of users (via e-mail or other means). The various trigger thresholds may be selected based on performance limits for the type and size of the building.

Significant research has been carried out by the author and others over the past several years to determine the feasibility of an automated post-earthquake damage assessment of instrumented buildings and establishment of a coherent set of techniques and methodologies to achieve the objectives of real-time damage detection and performance evaluation (DDPE). We call our approach to damage detection and performance evaluation "real-time" because it will take somewhere between a few seconds to a few minutes following a triggered event for our damage detection system to process the data recorded by various sensors installed in the building, and produce its damage and performance report and make it available to the authorized stakeholders in the form of an e-mail alert with links to or attachments containing a detailed status report.

DDPE provides a substantial and cost-effective incentive for building owners to instrument their buildings and benefit from the status reports that can be generated immediately after any extreme event (earthquake, fire, blast, windstorms, flooding, etc.) about the nature and extent of any possible damage and evaluation of whether the building can remain operational or not. With use of some of the techniques presented here even estimates of the cost and time of repairs can be made available to the building owner immediately following a triggering event.

Elimination or reduction of possible false alarms produced by various automated damage detection procedures has been a major concern of the author and other researchers (Naeim et al., 2005). Therefore, techniques have been developed to assess damage using several independent techniques and provide the degree of confidence in results in terms of probability of exceeding each damage state.

A robust DDPE system should be able to provide increasingly more accurate estimates of post-earthquake damage when more information is available regarding the building and its contents. With our approach, preliminary damage estimates are provided based on the sensor data and a general understanding of the building and its contents. More accurate damage estimates may be obtained if more detailed information regarding the structural system and contents are available such as detailed fragility curves for various components. Competent structural engineers can provide such information for a building by studying its construction documents.

The more specific information an automated damage detection system provides, the more useful it is. The damage estimates we provide can range from global (overall building state) to local (floor by floor or even component by component) and vary from deterministic measures which are useful to evaluate conformance to specific codes, guidelines, or standards, to probabilistic measures which are more accurate in terms of assessing the possible range of various damage states given the uncertainties inherent in building construction practice.

Miranda (2006) and Naeim et al. (2006) distinguish probabilistic measures as the most promising tools for real-time damage detection. Probabilistic measures rely on fragility functions to relate probability of damage exceeding a certain threshold to one or more demand parameters such as overall drift, interstory drift, floor acceleration or strain (Figure 2.1). Fragility functions are developed based on a variety of methods such as experimental test results, analytical simulations or expert opinion. Fragility functions are useful because they reflect the uncertainty inherent in performance of civil structures, their components, and contents. While absolute measures such as those suggested by building codes, guidelines and standards imply an unrealistic image of rapid performance changes when an absolute threshold is exceeded (see Figure 2.2), fragility functions provide a continuous range of performance where probability of damage increases as demand imposed on the system or components become larger.

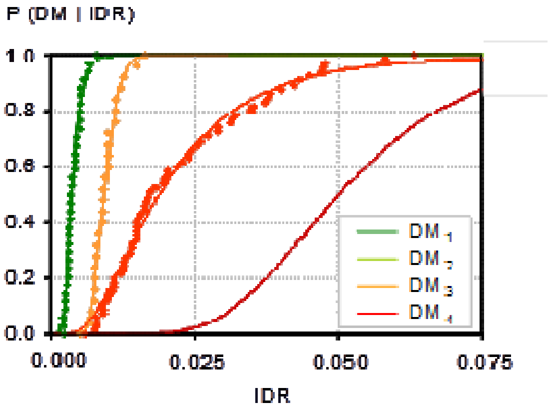

Figure 2.1. Fragility functions relate probability of damage severity to a measured demand parameter such as interstory drift ratio (Miranda 2006)

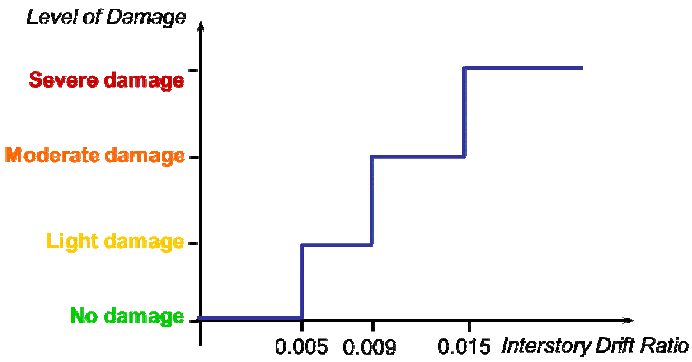

Figure 2.2. Unrealistic view of damage as a step function implied by building codes, and deterministic guidelines and standards (Miranda 2006)

Overall fragility functions form the basis of loss estimation deployed in FEMA's HAZUS-MH loss estimation methodology and software system. More detailed fragility functions for various systems and components have been developed by PEER/NSF researchers. Most recently hundreds of detailed fragilities are under development by the FEMA funded ATC-58 project for use in the new generation of performance based design. These newly developed fragilities have the potential to significantly increase the reliability and usefulness of re-al-time damage detection technologies

3. HOW DOES REFLEXX WORK?

3.1. The Basics

In a health-monitored structure a variety of sensors are continuously receiving and processing data relevant to building movements and its dynamic characteristics. Once a pre-determined threshold of excitation set for one or more sensors is exceeded, all sensors start recording the subsequent excitations for a predetermined time period (usually a few minutes) or until the level of excitation stays under the triggering threshold for a set amount of time. Digital sensors usually have a certain amount of pre-event memory which is used to buffer valuable data received immediately before the trigger threshold was reached. This assures a complete set of sensor records can be obtained which virtually span excitations experienced by the structure from the initial so-called "rest status" to the final rest status and therefore provide realistic boundary conditions necessary for conducting accurate subsequent computations.

Once an event is recorded (either manually or via the triggering mechanism), the REFLEXX system processes that information and within a few minutes issues a status report regarding the event and its effects on the structure (Figure 3.1). In order to do this, the REFLEXX system needs to know about the layout of the structure, the spatial position of sensors in and around the structure, various damage thresholds in deterministic and/or probabilistic manners, and what sensors or combination of sensors it should use and how to calculate the input into different damage detection and performance evaluation functions, and how to organize and present its reports and summaries to the pre-event identified stakeholders.

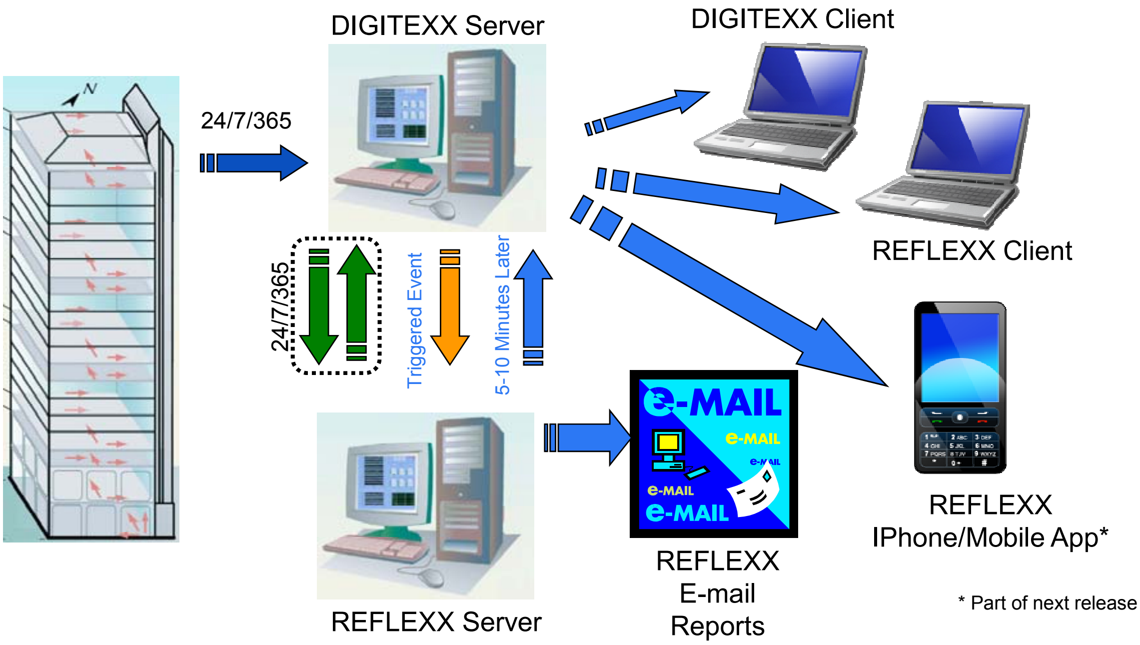

Figure 3.1. Flow of REFLEXX Operations

It is crucial for proper functioning of a reliable DDPE system that highly reliable data transmission means and protocols exist between the health monitoring system and the DDPE system. The reliability of this vital data transmission high-way, in terms of both its hardware and software components, needs to be tested and verified by an established program for triggering artificial events in order to test the system manually, periodically, and/or randomly. It is also important that each event and its nature (manually triggered or real) be archived with an accurate time stamp and a reference to the characteristics and models of the structure at the time of the event. It is possible for buildings, their properties, sensor layouts, and contents to change over time. Therefore, application of information received from sensors at one time may not be applicable to the same building at other times unless proper adjustments are made in representation of the building, or the dataset for the building at the time is preserved with the archived sensor data.

In order for the DDPE system to be useful to a wide range of stakeholders the type, format and content of its automatically generated e-mail alerts and reports must be highly customizable to fit the exact needs of various individuals and entities receiving the information. A standalone or client version of DDPE must be al-so made available to engineers and building managers so that they can review and compare results obtained from various events and suggest refining the fragility specifications and or the corresponding thresholds utilized.

3.2. Sensor Types

A complete DDPE system must be able to accommodate and utilize data obtained from a wide variety of sensors including but not limited to accelerometers; velocity meters such as wind speed meters; displacement sensors such as strain meters, tilt meters and LVDTs (linear variable differential transformers); intrusion detection sensors; and environmental sensors (temperature, wind speed and direction measurements).

This flexibility is necessary to integrate the DDPE system with other monitoring systems already installed at the facility (such as security systems, fire alarms, elevator monitoring equipment, etc.) and therefore add to the value of DDPE as a component of systems that together make a smart building system.

3.3. Spatial Distribution of Sensors

Distribution of sensors throughout the structure requires a careful consideration of building properties, zones of expected damage, and location of critical or sensitive equipment in and around the building. The instrumentation plan for the structure must be established in consultation with a structural engineer who knows the building and is knowledgeable about building instrumentation technologies. In this paper we concentrate on distribution of accelerometers as they are the most commonly used sensors utilized in seismically instrumented buildings.

Allocation of sensors requires a balancing act between the desired information and the available budget for instrumentation. If a building floor is instrumented, in the simplest case of a rigid diaphragm floor, three sensors are required to measure the movement at any location on the floor (Naeim et al. 2005) as explained below. Let us consider a sensor distribution as shown in the rectangular floor as shown in Figure 3.2.

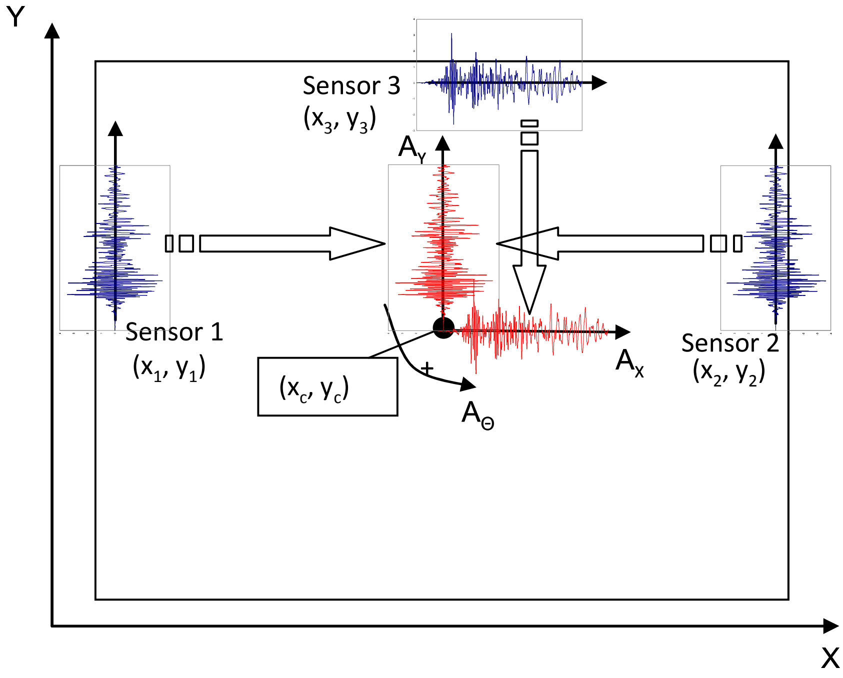

Figure 3.2. Typical sensor layout on a rigid diaphragm rectangular floor

This floor has three sensors with the coordinates (x_1, y_1), (x_2, y_2) and (x_3, y_3). For every time step these sensors report displacements A_1, A_2 and A_3 in their respective directions. Let us assume that the floor's geometric centre has coordinates (x_c , y_c). The relation between sensor displacements and those of a point with coordinates (x_c , y_c) on the floor is

$$\begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & (x_1 - x_c) \\ 0 & 1 & (x_2 - x_c) \\ 1 & 0 & -(y_3 - y_c) \end{bmatrix} \begin{bmatrix} A_x \\ A_y \\ \theta \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} A_x \\ A_y \\ \theta \end{bmatrix} = \begin{bmatrix} \frac{y_c - y_3}{x_2 - x_1} & \frac{y_3 - y_c}{x_2 - x_1} & 1 \\ \frac{x_2 - x_c}{x_2 - x_1} & \frac{x_c - x_1}{x_2 - x_1} & 0 \\ -\frac{1}{x_2 - x_1} & \frac{1}{x_2 - x_1} & 0 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \\ A_3 \end{bmatrix}$$

The same formulas may be used to obtain displacements of any other point on the rigid floor by substituting the coordinates of that point instead of (x_c, y_c).

Complicated (non-rigid) floor layouts may be accommodated by dividing them into a series of zones where the rigid diaphragm assumption may be locally justified. Also notice that sensors may be shared among zones as justified, reducing the number of sensors needed. For example, in the floor layout shown in Figure 3.3 consisting of 4 zones, probably only five or six sensors instead of 12 (4x3) are needed to get a good idea about the displacements anywhere on the floor.

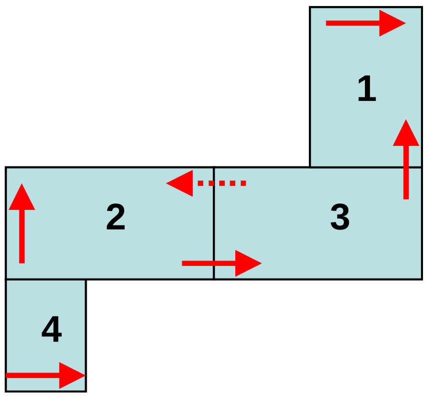

Figure 3.3. Complicated floor layouts may be divided in simpler zones for establishing an efficient sensor layout

Using the above approach the motion at any point on the floor may be instantaneously calculated from the sensor data and as such the demand parameters for components of interest are calculated based on their specified location and orientation (if necessary). In an ideal world every floor of a building would be instrumented as explained above. However, the cost of instrumenting every floor of the building may become prohibitive particularly for high-rise structures. A Variety of interpolation schemes (Naeim et. al 2005) and/or Observer schemes based on control theories (Bernal and Hernandez 2006) may be utilized to approximate the response of floors in between the instrumented floors. Rough guidelines for deciding the number of sensors per instrumented floor are provided in Figure 3.4.

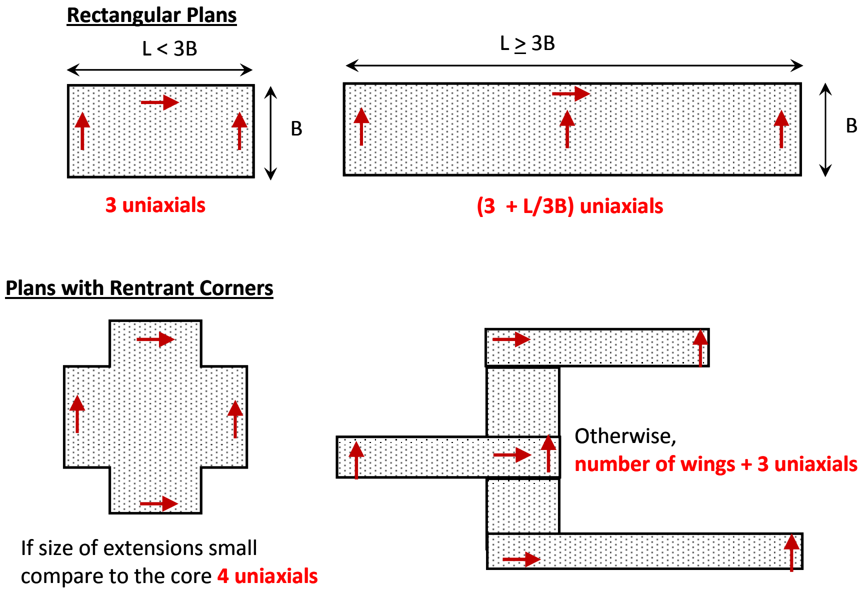

Figure 3.4. Accelerometer distribution over the plan

Bernal and Nasseri (2009) have documented the issues with simple interpolation techniques (linear, cubic spline, etc.) which may result in substantial overestimating of accelerations and forces if the number of floors instrumented are not sufficient to represent building vibration modes that have significant contributions to the total response of the building. One thing to note is that regardless of the degree of accuracy of an interpolation scheme, a scheme cannot produce information that is not there. In other words, a good interpolation scheme can provide reasonable estimates of the status of an un-instrumented floor as long as the status of that floor can logically be determined from the status of the instrumented floors. Therefore, if systems or components located in between two nonadjacent instrumented floors suffer damages that exceed those at the instrumented floors used for interpolating results, the interpolated results will be inherently unreliable for establishing damage suffered by those systems or components. As a result, it is very important to select instrumented floors carefully and include floors of critical importance in the list of floors to be instrumented.

3.4. Classification of Performance Evaluation Techniques and Measures

A robust DDPE system should be able to utilize a variety of techniques and thresholds for real-time performance evaluation of buildings. These techniques are not mutually exclusive and are often complimentary to each other and in combination can provide a better local and global perspective on the status of the building under consideration. From the standpoint of methodology, the thresholds may be categorized as deterministic, probabilistic or hybrid (a mixture of measurements and analyses). In terms of the degree of abstraction, the measures may be divided into global, floor-by-floor, and component-by-component categories.

3.4.1. Deterministic Measures

Deterministic thresholds are useful in monitoring compliance with clearly established limits specified by design or performance criteria or governing code, standard, or guideline provisions.

Global deterministic thresholds may be established in terms of overall transient or residual displacement or drift ratio experienced by a building or other thresh-olds that relate to the overall building response. Floor-by-floor deterministic thresholds may be established in terms of code specified or project specifications established limits on story drifts, accelerations, or other entities of interest defined in a floor-by-floor sense. Finally, component-by-component deterministic thresh-olds may be established based on manufacturer specifications or code provisions for satisfactory performance of mechanical equipment in terms of floor acceleration or spectra at the location of the equipment, or acceleration at the top of the equipment, racking, velocity or other demand parameters of relevance. For long span roofs and trusses and for shear walls or concrete columns, strain measures may be used as indicators of behaviour status. Again, a robust DDPE system must accommodate a variety of demand parameters which could be used for a whole host of different systems, components, and contents of a building.

3.4.2. Probabilistic Measures

Probabilistic thresholds are defined in terms of fragility specifications and may be defined as global, floor-by-floor, or component-by-component measures. HAZUS-MH (FEMA-2003a) generic structural and nonstructural fragility functions are examples of simple global fragility functions which may be adopted and modified to reflect the specific properties of the building system being considered. One method to develop and/or refine global fragilities for specific buildings is given in the HAZUS-MH AEBM Technical Manual (FEMA-2003b). Other methods for establishing such fragility functions range from application of simple procedures based on pushover analyses such as SPO2IDA (Vamvatsikos and Cornell 2005) to a complicated series of linear or nonlinear analyses of the building.

Sources of floor-by-floor and component-by component fragility specifications include various university reports including those issued by the Pacific Earthquake Engineering Research Center (PEER) in recent years. A particularly important and in many ways unique source of component fragility specifications is the FEMA-sponsored ATC-58 project and its software system PACT (Performance Assessment Calculation Tool). As a part of the ATC-58 project detailed fragility specifications including estimated cost of repairs and associated downtime (repair time) for more than 600 structural and nonstructural components have been compiled and will be made available to the public at the conclusion of the ATC-58 project.

3.4.3. Hybrid Monitoring and Analyses Methods

It is possible to link a DDPE system to simple or sophisticated computer models of the building to either calibrate the model with the results obtained from instrumentation and/or provide live channels of communication between the DDPE system and the analytical model(s) of the building to assess stress and strain at various locations of the building. This is akin to contemporary hybrid testing methods utilized in structural laboratories.

4. CONCLUSIONS

This paper demonstrated the utility and application of the Real-Time Damage Detection and Performance Evaluation system when used in conjunction with a Real-Time Structural Health Monitoring System.

Considering the adverse effects an event can have on the performance, safety, or operability of a building or a portfolio of buildings, owners and managers of such buildings are in desperate need of reliable information regarding the status of their facilities.

While having an engineer in place before an extreme event happens may reduce the wait time for visual inspection and assessment from weeks to days, many buildings need to make a decision within minutes --not days or weeks -- whether their building should remain occupied and operational. Real-time structural health monitoring when combined with state-of-the-art damage detection and performance evaluation methodologies are currently the only method to satisfy that dire need of building owners and managers. The DDPE system effectively and efficiently addresses this need providing an assessment within minutes following an event.

A robust DDPE system should be able to provide increasingly more accurate estimates of post-earthquake damage when more information is available regarding the building and its contents. With our approach, preliminary damage estimates are provided based on the sensor data and a general understanding of the building and its contents. More accurate damage estimates may be obtained if more detailed information regarding the structural system and contents are available such as detailed fragility curves for various components. Competent structural engineers can provide such information for a building by studying its construction documents. The DDPE system presented in this paper satisfies these requirements in an efficient and economical manner.

REFERENCES

American Society of Civil Engineers (2007), Seismic Rehabilitation of Existing Buildings, ASCE Standard No. ASCE/SEI 41-06.

Bernal, D. and Hernandez, E. (2006), A Data-driven Methodology for Assessing Im-pact of Earthquakes on the Health of Building Structural Systems, The Structural Design of Tall and Special Buildings, 15, 1, pp. 21-34, (F. Naeim, ed.), Wiley Inter-Science, London.

Bernal, D. and Nasseri. A. (2009), Schemes for Reconstructing the Seismic Response of Instrumented Buildings, http://www.consrv.ca.gov/cgs/smip/docs/seminar/SMIP09/Documents/Z2_Paper_Bernal.pdf.

Celebi, M., Sanli,A., Sinclair,M, Gallant, S., and Radulescu, D. (2004), Real-Time Seismic Monitoring Needs of a Building Owner—and the Solution: A Cooperative Effort. Earthquake Spectra, May, pg 341, Earthquake Engineering Research Institute, Oakland, CA.

Federal Emergency Management Agency (FEMA) 2000, Prestandard and Commen-tary for the Seismic Rehabilitation of Buildings, FEMA-356, Washington, D.C.

Federal Emergency Management Agency (FEMA) 2003-a, HAZUS-MH Technical Manual, Washington, D.C.

Federal Emergency Management Agency (FEMA) 2003-b, HAZUS-MH Advanced Engineering Building Module -- Technical and User’s Manual, Washington, D.C.

Miranda, E. (2006), Use of Probability-Based Measures for Automated Damage As-sessment, The Structural Design of Tall and Special Buildings, 15, 1, pp. 35-50, (F. Naeim, ed.), Wiley InterScience, London.

Naeim, F. (1997), Instrumented Buildings Information System for January 17, 1994, Northridge, California earthquake, John A. Martin & Associates, Inc., Version 1.0.

Naeim, F., Hagie, S., Alimoradi, A., and Miranda, E. (2005), Automated Post-Earthquake Damage Assessment and Safety Evaluation of Instrumented Buildings, A Report to California Strong Motion Instrumentation Program, JAMA Report No. 2005-10639, John A. Martin & Associates, Inc., Los Angeles, CA.

Naeim, F., H. Lee, S. Hagie, H. Bhatia, A. Alimoradi, E. Miranda, (2006), Three-dimensional analysis, real-time visualization, and automated post-earthquake damage assessment of buildings, The Structural Design of Tall and Special Buildings, 15, 1, pp. 105-138, Wiley InterScience, London.

Naeim, F., S. Hagie, A. Alimoradi, and E. Miranda, (2006). Automated Post- Earth-quake Damage Assessment of Instrumented Buildings, in Advances in Earthquake Engineering for Urban Risk Reduction, S.T. Wasti and G. Ozcebe (eds.), pp. 117-134, Springer.

Naeim, F. and Hagie, S. (2007), PACT Beta User Guide, Applied Technology Coun-cil, Redwood City, CA, May.

Naeim, F. and Hagie, S. (2010a), PACT 2 Alpha User Guide, Applied Technology Council, Redwood City, CA. February.

Naeim, F. and Hagie, S. (2010b), PACT 2 Technical Manual, Applied Technology Council, Redwood City, CA, February.

Vamvatsikos D., Cornell C.A. (2005), Direct estimation of the seismic demand and capacity of MDOF systems through Incremental Dynamic Analysis of an SDOF Ap-proximation, ASCE Journal of Structural Engineering, 131(4): 589-599.