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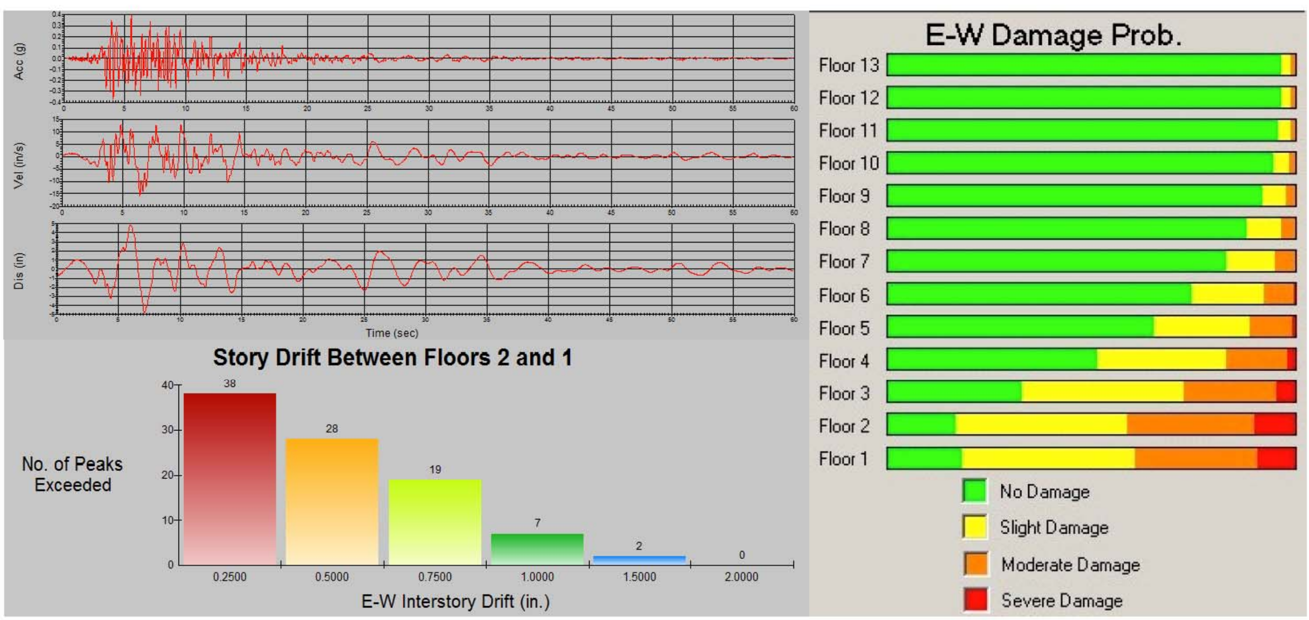
Report No. 13115-2011

REAL-TIME DAMAGE DETECTION AND PERFORMANCE EVALUATION FOR BUILDINGS

-- A White Paper --



REFLEXX Smart System BUILDINGS

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Prepared for:

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May 2011

This White Paper was prepared under a cooperative agreement between John A. Martin & Associates, Inc. (JAMA) and Digitexx Data Systems (Digitexx).

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INTRODUCTION

Immediately following an event that could aversely 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.

Following major events, due to the large number of buildings requiring inspections and evaluations, it may takes days or weeks before status of a building can be assessed relying on traditional approaches. For example, City of San Francisco advises building owners not to wait for free inspections after earthquakes because it may take the City inspectors or volunteers somewhere between 3 to 10 days to visit a building for a rapid safety assessment[*]. This is the reason why a number of cities such as San Francisco have established programs to allow building owners to register their buildings into a database. This allows engineers hired by the owners prior to earthquake who are familiar with the building to perform such assessments faster following an earthquake.

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.

[*] City and County of San Francisco, Department of Building Inspection, *Building Owners: WHY BORP?*, http://sfdbi.org.

In October 2010 *John A. Martin & Associates, Inc*. (*JAMA*), a leading structural and earthquake engineering consulting firm, and *Digitexx* a leading real-time structural health monitoring services company entered into a collaboration agreement to join forces in developing an state-of-the art system for real-time damage detection and performance evaluation (DDPE) code named REFLEXX Smart System for Buildings. Joint work under the first phase of this agreement is currently underway resulting in the first version of REFLEXX to be made available via *Digitexx* to its clients by July 2011.

REFLEXX 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 implemented in REFLEXX even estimates of the cost and time of repairs can be made available to the building owner immediately following a triggering 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.

This White Paper begins with introducing the utility of real-time structural health monitoring and continues with a review of various techniques for real-time damage detection and performance evaluation based on the information supplied by a properly configured and installed structural health monitoring system. It will then proceed with describing the process and methods currently under development for the REFLEXX system. Finally, examples of application that can be readily used once the REFLEXX system is deployed are presented to highlight the utility and appeal of this system.

Founded in 2000, *Digitexx* is the first private company to develop real-time structural health monitoring systems for a variety of industries and applications including: bridges, buildings, campuses, windmills, oil rigs, dams, levees and other structures. Digitexx's innovative earthquake response locational algorithm for tall buildings is jointly patented with Caltech. When properly configured, the *Digitexx* system is capable of measuring and responding to both natural and man-made events such as: earthquakes, wind, explosions and accidental heavy impacts.

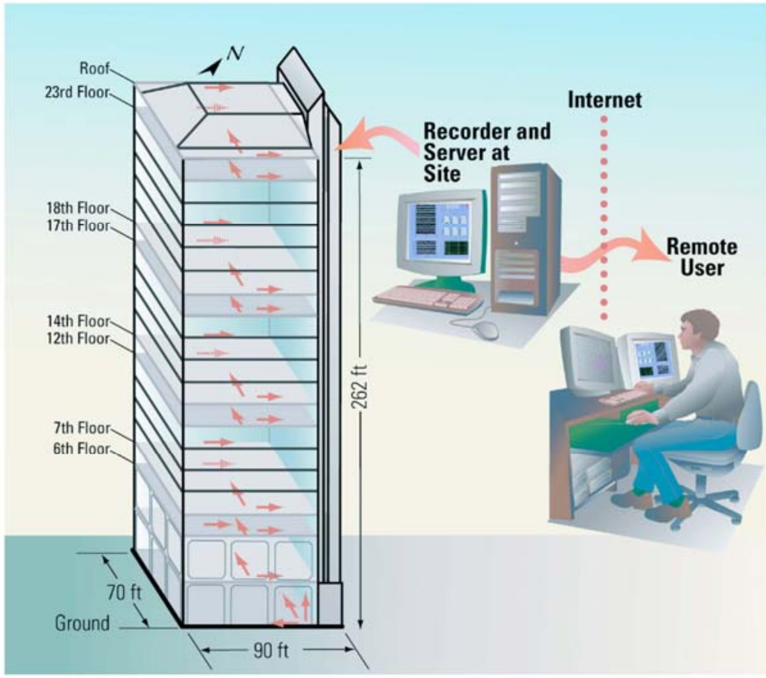
Founded in 1953, *JAMA* is one of the largest privately-owned structural engineering firms in the USA. *JAMA* draws upon the Martin Associates Group's corporate network of 12 offices throughout the United States and China. The firm completes structural designs for an annual average of 60 million square feet of new construction worldwide. The firm's staff maintains professional structural engineering registrations in all 50 states, as well as Puerto Rico, Guam and China. *JAMA R&D* has successfully obtained and conducted a variety of sponsored research grants and contracts for many federal, state and local entities such as the United States Geological Survey, Applied Technology Council, State of California, and County of Los Angeles. Particularly relevant to this White Paper is the exhaustive research conducted by *JAMA R&D* for State of California, California Geologic Survey, Strong Motion Instrumentation Program (SMIP) to determine the feasibility of an automated approach to post-earthquake damage assessment of instrumented buildings and establishment of a coherent set of techniques and methodologies to achieve the objective of automated post-earthquake damage assessment (Naeim et al., 2005, 2006) and current work on development of performance assessment calculation tool (PACT) for Applied Technology Council (ATC) and FEMA (Naeim et al., 2007, 2010).

REAL-TIME STRUCTURAL HEALTH MONITORING

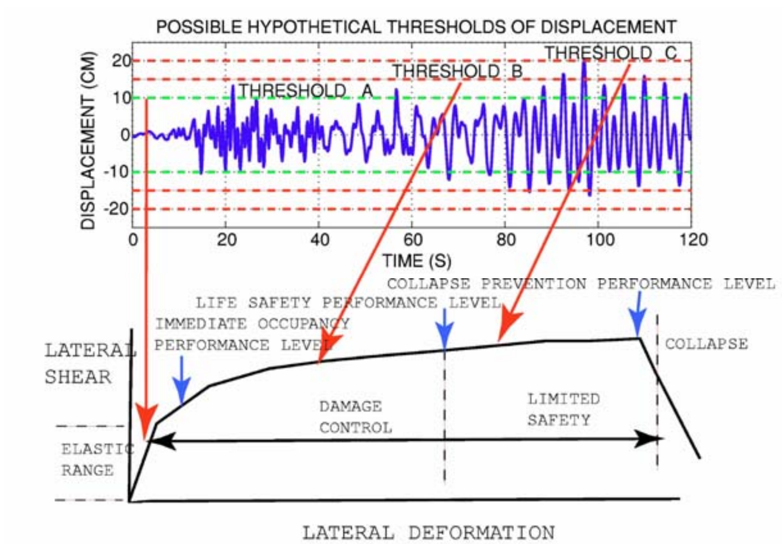
Real-time structural health monitoring is not a promise. It is an existing technology that has been deployed and advanced successfully by *Digitexx* and a number of its competitors on many buildings, bridges, and other types of structures.

The *Digitexx* monitoring system is 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 instumented 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.

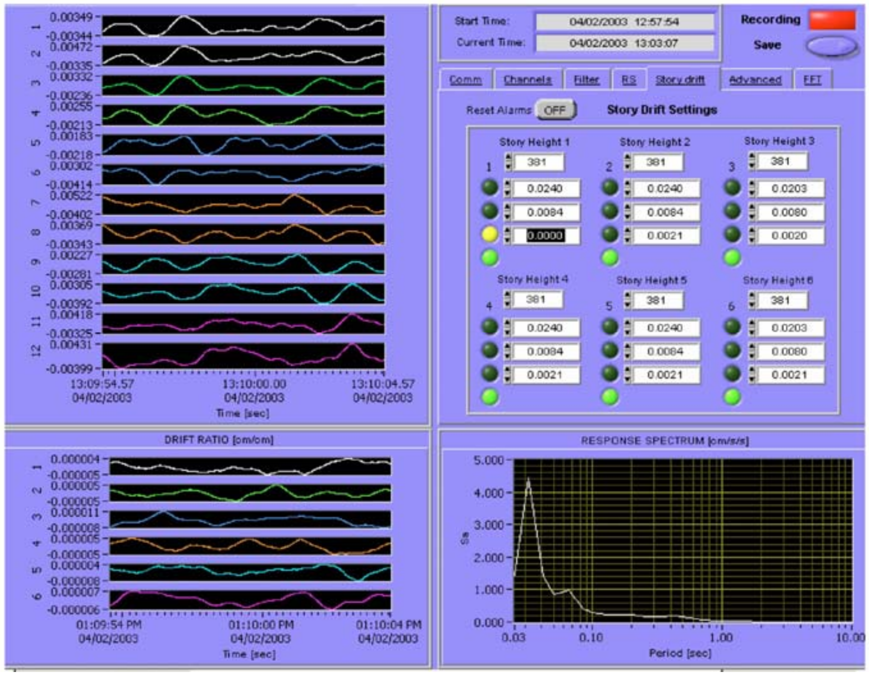
One such application of *Digitexx* monitoring system has been documented by Celebi et al. (2004) where sensors were installed on multiple pairs of building floors to measure the relative displacement of adjacent floors (interstory drift) which was then related to performance of the building using damage thresholds specified in documents such as FEMA-356 or ASCE 41 performance based design guidelines.



General schematic of Digitexx data acquisition and transmittal for seismic monitoring of a 24 story Building (from Celebi et al. 2004).



Use of limits identified by performance based design guidelines such as FEMA-356 or ASCE 41 for classification of damage in the seismic monitoring of a 24 story Building (from Celebi et al. 2004).



Screen snapshot of Digitexx client software display showing 12-channel (six pairs with each pair a different color) displacement and corresponding six-drift ratio (each corresponding to the same color displacement) streams. Also shown to the upper right are alarm systems corresponding to thresholds that must be manually input. The first threshold for the first drift ratio is hypothetically exceeded to indicate the starting of the recording and change in the color of the alarm from green to yellow (from Celebi et al. 2004)

Another example of real-time structural health monitoring by installation of sensors at every floor of the 10 story Caltech Milikan Library building involving the technology patented jointly by Caltech and Digitexx is documented by Prof. Wilfred Iwan.

Photo of the Caltech Milikan Library building and the screen snapshot of the proprietary Digitexx/Caltech client software utilized for real-time structural health monitoring of the building.

REAL-TIME DAMAGE DETECTION AND PERFORMANCE EVALUATION

Background

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). Representative publications documenting such efforts are cited at the end of this White Paper.

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 as described later in this document.

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.

Several approaches have been proposed for automated damage detection including use of:

- System identification techniques;
- Wavelet analyses;
- Use of Design Based approaches;
- Use of probabilistic measures such as system-wide fragility curves such as those suggested by HAZUS-MH or detailed component fragilities as developed by PEER/NSF or under development by the ATC-58 project.
- Using a combination of the above techniques

Evaluation of Various Methodologies

System Identification Techniques

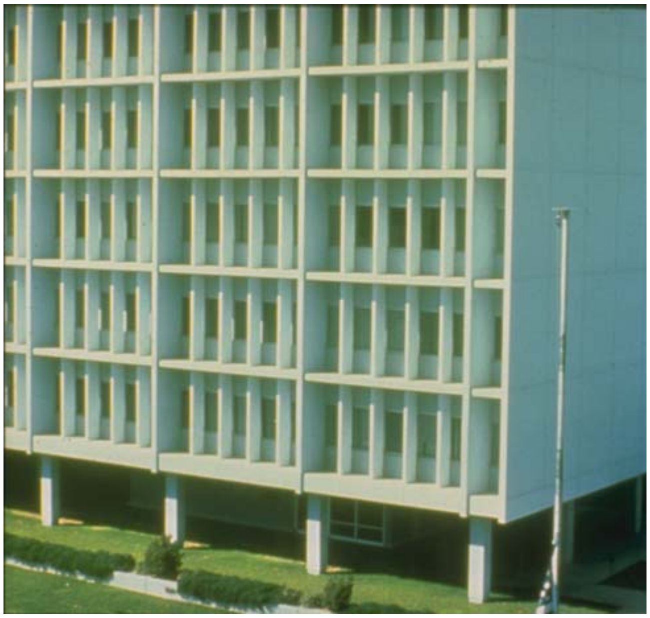
System identification techniques compute and track changes in the dynamic characteristics of the building (periods of vibration, damping, mode shapes, etc.) and try to relate changes in these characteristics to potential damage. Naeim (1997) applied this technique to 20 instrumented buildings that suffered various degrees of damage during the 1994 Northridge earthquake and concluded that although period elongation can be demonstrated for many buildings that experienced damage, it was difficult to correlate the degree and specific types of damage to these changes. Later in 2005 Naeim et al. applied a novel system identification technique to more than 40 instrumented buildings that have experienced more than one earthquake and reached similar conclusions. The primary reason for this is that a variety of things such as soil conditions, moisture, temperature and participation of nonstructural systems and components can contribute to changes in dynamic characteristics of a building and outside a laboratory setting it is very difficult to cross correlate these changes to specific damage.

As an example, consider the Imperial Valley County Services Building (instrumented by CSMIP) which was seriously damaged during the 1979 Imperial Valley earthquake and later demolished.

Naeim et. al (2005) performed system identification using GA optimization and showed that in the East-West direction indicates that the fundamental period of this building which was about 0.7 sec. doubled to 1.5 sec. towards the end of the record. Although damage may be suspected from this drastic change in dynamic characteristics of the building during the earthquake, failure at the base of the columns cannot be directly inferred from this change without some additional information.

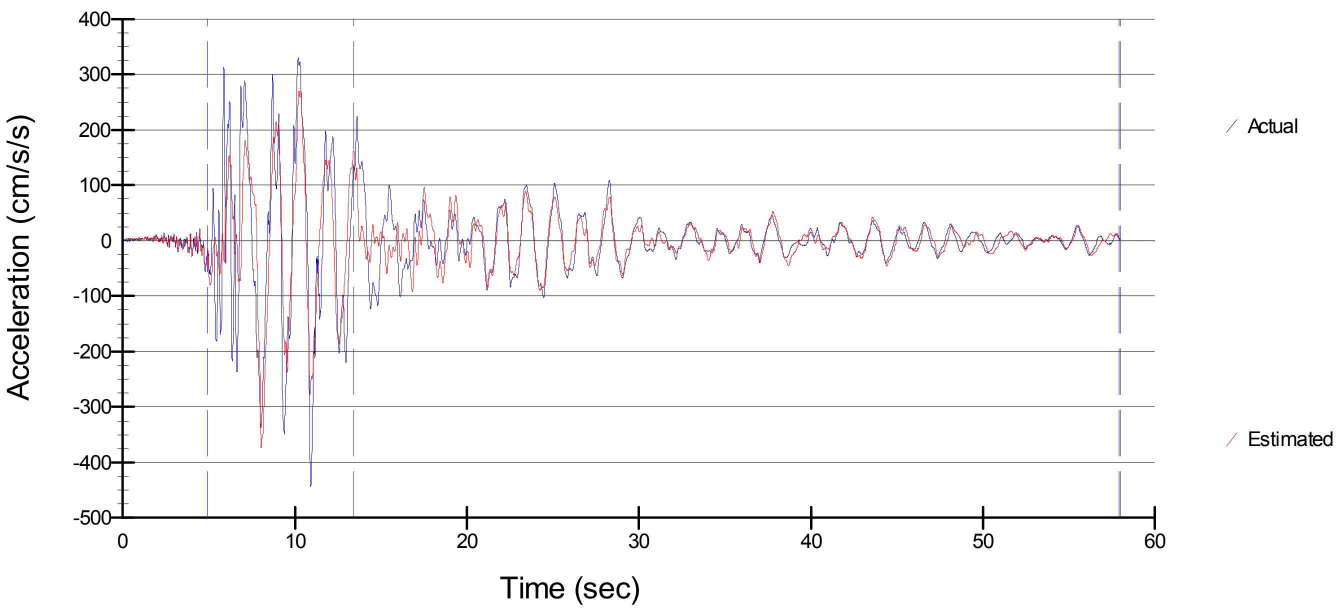
Imperial Valley Services Building

(Photo Credits: BAREPP and USGS)



(a) A view of the building

(b) Failure of columns at the base



Recorded and GA identified response of the Imperial Valley Services Building

Wavelet Analyses

A wavelet is virtually any waveform that has limited duration and zero average. During decomposition, a given signal is split into two signals: *Approximation* and *Detail*. The *Detail* depicts the sudden changes in frequency content and is of potential use in detecting damage.

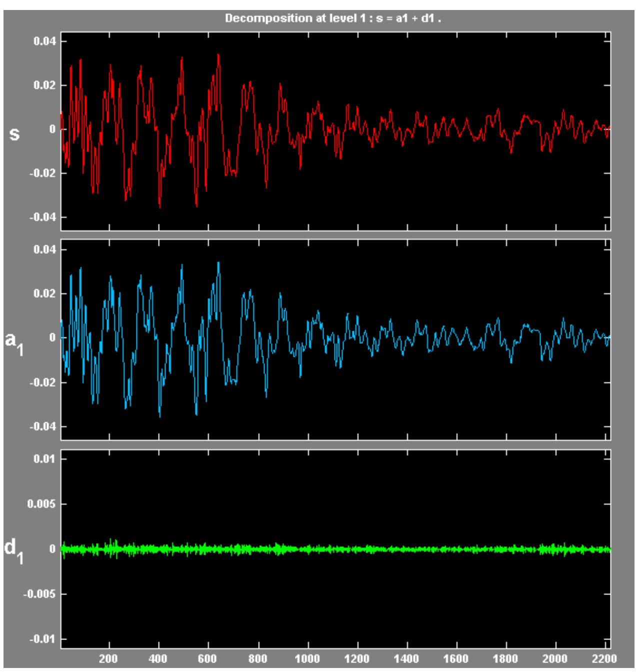
Several researchers have suggested the use of wavelets for detecting structural damage (see Hou, Noori and Amand 2000 for a useful summary). The problems with using wavelets for automated damage detection, however, are numerous. First, it is difficult to assign a particular level of amplitude in *Detail* to the onset of damage. Second, it is even more difficult to distinguish various levels of damage to different levels of *Detail* amplitude. Finally, there is always a chance for a particular peak in the *Detail* to relate to something other than structural damage and therefore resulting in a false alarm. Wavelets are useful, however, if wavelet information regarding the undamaged status of the building from a prior event is available and can be used as a baseline to distinguish the sudden change in behavior of the building during a subsequent damaging earthquake. Therefore, we believe that at this time wavelet analysis can be used only to confirm results obtained by other methods and not as a primary damage detection tool.

This auxiliary use of wavelet analysis is best demonstrated by an example. Consider the 13-Story Commercial Building in Sherman Oaks, CA, instrumented by the California Strong Motion Instrumentation Program (CSMIP) that was moderately damaged during the 1994 Northridge earthquake but was undamaged during the 1992 Landers earthquake. Wavelet analyses results for a sensor which was located close to the zone of most severe damage and the corresponding damage is shown below. The rich high-frequency content and a sudden spike in the detail (shown by an arrow) of the response under Northridge can be viewed as an indicator of damage but level of damage cannot be ascertained from this information.

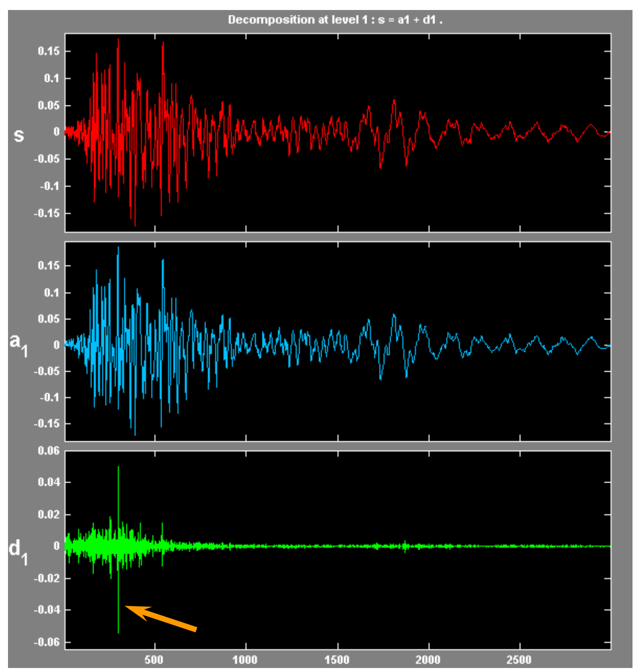
13 Story Sherman Oaks Building and 1994 Earthquake Damage

Wavelet Analysis of a Sensor -- 13 Story Sherman Oaks Building

1992 Landers Earthquake (no damage)

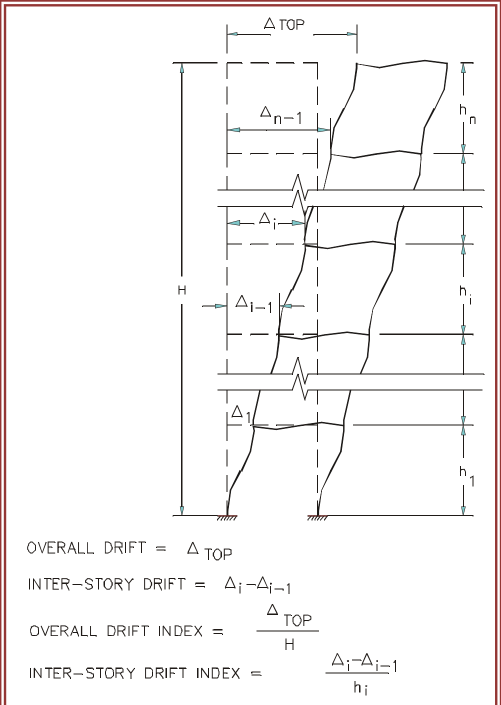


1994 Northridge Earthquake (some damage)



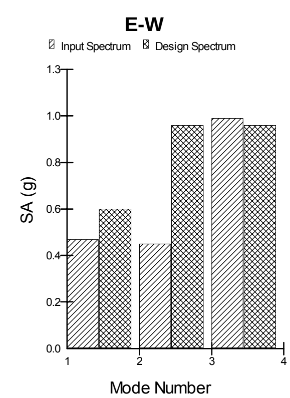
Design-Based Measures

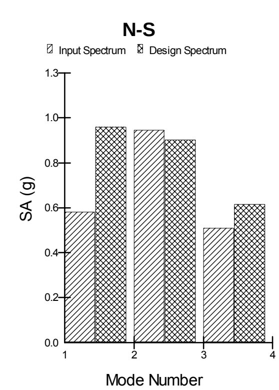
It has been shown that except for the maximum inter-story drift ratios other simple or "design based" majors have very little use, if any, for damage assessment of a building (Naeim 1997 and 1998; Naeim and Lobo 1998). There are several reasons for this. First, the design values by their nature are intended to be conservative and exceeding them does not necessarily indicate damage. Second, the force-based design values are based on empirical and sometime arbitrary reduction factors that are based on pure judgment and often change after each earthquake. Third, to use any design-based value properly, one needs a detailed knowledge of the force levels a particular building was designed for, the engineering details utilized, level of workmanship provided, specific strengths and weaknesses of the particular structural system, configuration, and the geometry utilized. None of this information is available immediately following an earthquake for a typical instrumented building.



Definition of Drift

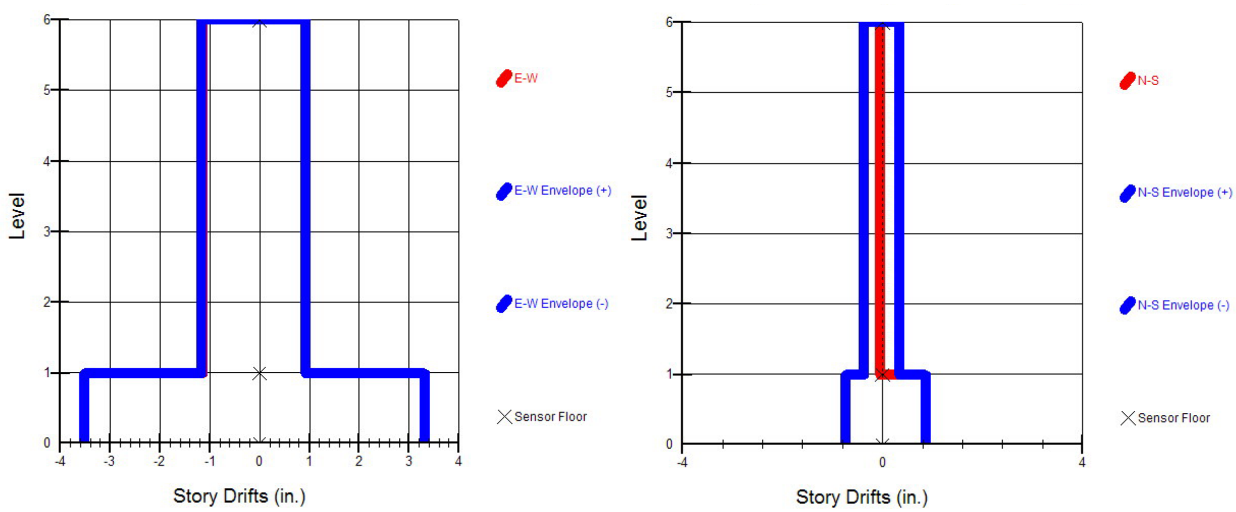
An example would best illustrate the limitations of utility of design-based indicators towards damage assessment of buildings. Response spectrum analysis is a technique that is commonly used in analysis and design of buildings. Consider the same Imperial Valley County Services Building which was introduced in the previous section.





Comparison of input elastic spectra at the base with a typical unreduced code spectrum for seismic zone 3, where this building was located, provides little to work with as far as damage assessments are concerned. First, the elastic demand/capacity ratios in the E-W and N-S directions look about the same. Second, comparison of modal base shear demand and assumed capacities are not far apart from each other. Third, no information pertaining to the significant attributes of the building particular to this structure, such as irregularity, discontinuity of shear walls can be inferred from spectral comparisons. Fourth, the E-W and N-S picture do not vary by much although the building is significantly weaker in the E-W direction. Finally, no information regarding the possible distribution of damage throughout the height of the structure can be obtained.

Instantaneous and maximum values of interstory drifts for instrumented buildings after an earthquake can be easily and immediately estimated. These drift values are of immense value in automated damage assessment. A glimpse at the E-W and N-S interstory drifts for the same building reveals that the drift demands in the E-W direction were significantly larger than those in the N-S direction. Furthermore, a drift of 3.5 inches at the first floor is inferred from sensor data in the E-W direction while the maximum drifts in the upper floors are limited to about 1.0 inch. This information can be directly related to significant damage in the E-W direction at the first floor (where damage actually occurred).



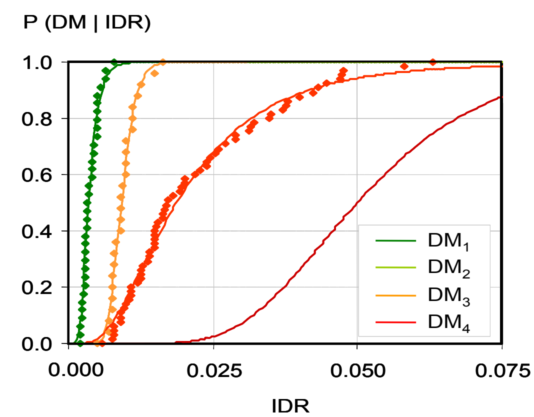
(a) E-W *(b) N-S*

Maximum inter-story drifts calculated from sensor recordings in the E-W and N-S directions of the Imperial Valley Services Building suggest significant damage in the E-W direction (where damage actually occurred).

Use of Probabilistic Measures

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.

Fragility functions are developed based on a variety of methods such as experimental test results, analytical simulations or expert opinion.



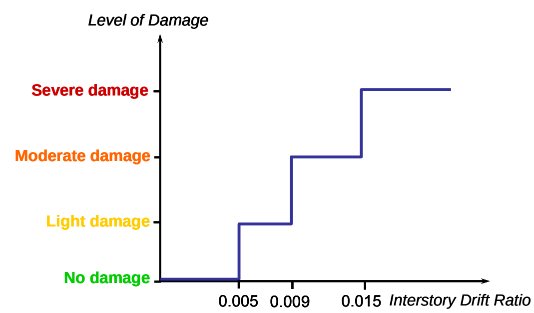
Fragility functions relate probability of damage severity to a measured demand parameter such as interstory drift ratio (IDR)

Aslani and Miranda (2005); Miranda (2006)

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, fragility functions provide a continuous range of performance where probability of damage increases as demand imposed on the system or components become larger.

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

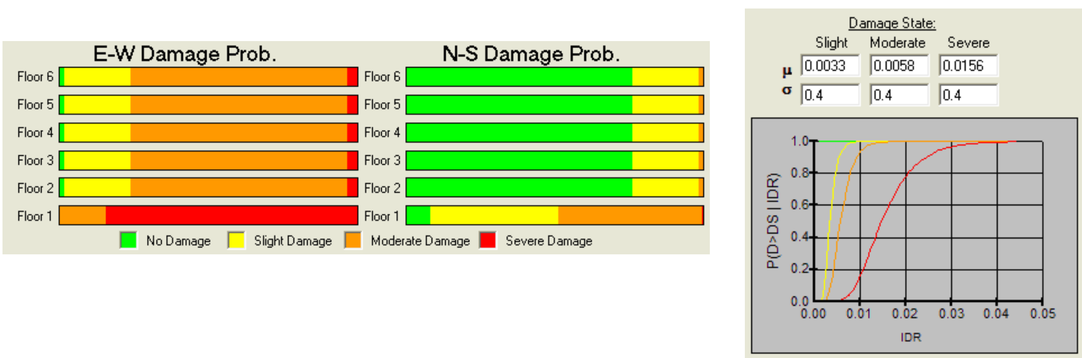


Unrealistic view of damage as a step function implied by building codes, and deterministic guidelines and standards.

Miranda (2006)

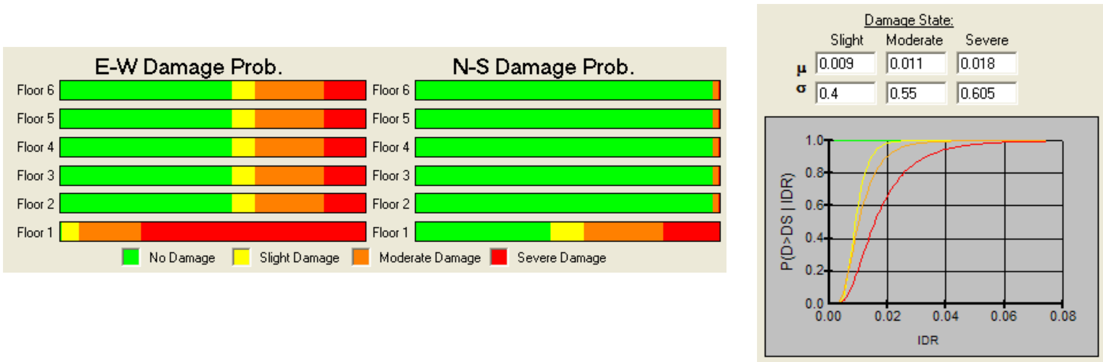
development by the FEMA funded ATC-58 project for use in the new generation of performance based design. These newly developed fragilities have the potential to significantly increase the reliability and usefulness of real-time damage detection technologies.

As an example, let us take a look at use of probabilistic measures to the Imperial County Services building which was introduced before. If we use HAZUS-MH fragility curves based on interstory drifts for this type of building (C1M or C2M, older building), we obtain 85% probability of severe damage and 15% probability of moderate damage at the first floor in the E-W direction. This is exactly where the column failures occurred. The damage at the upper floors of this building was limited as the failure of the first floor columns produced a relatively rigid pin-based block. This is also reflected in these damage estimates.



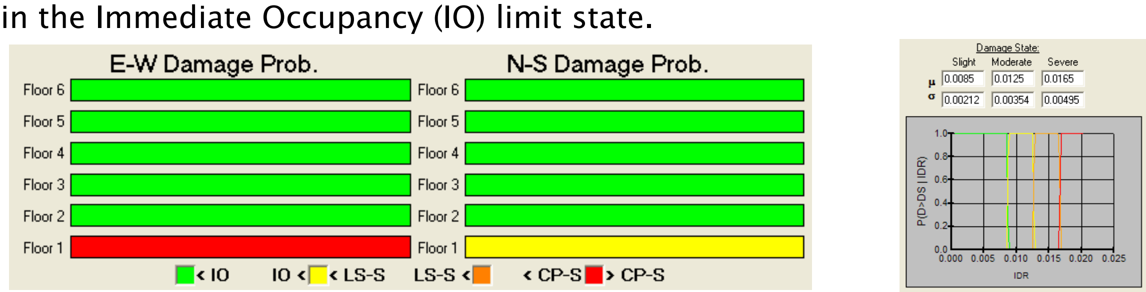
Damage probability established based on HAZUS-MH drift-based fragility curves for older concrete buildings clearly identifies the first floor in the E-W direction as the zone of severe damage.

Use of the PEER/NSF fragility curves for flexural behavior of nonductile R/C columns provides similar useful information. Based on this approach, the probability of severe damage to the first floor columns in the E-W direction is 74% and in the N-S direction is 19%. The probability of the severe column damage in upper floors is only 14% in the E-W direction and 0% in the N-S direction. The significance of the component fragility curves is that the probability of damage based on various damage mechanisms and various components can be estimated. For example, using the fragility curves developed for old R/C beam-column joints, one obtains that the probability for beam-column joint severe damage throughout this building is 0% while the probability of slight damage to these joints is 81% at the first floor in the E-W direction.



Damage probability established based on PEER/NSF fragility curves for nonductile R/C columns under large gravity loads clearly identifies the first floor columns in the E-W direction as the zone of severe damage.

Even FEMA-356 tables intended for nonlinear performance analyses such as Table 6-8 of FEMA-356 can be cast into a fragility curve for the purposes of automated post-earthquake damage assessment. For example, one can assume a certain level of elastic drift and apply some adjustment factors to take into consideration the inherent conservatism of FEMA-356 tabulated limit states. For instance, if we assume the building can take 0.005 of interstory drift angle within its elastic limit, do not apply any adjustment factors, and use the mean secondary values provided in FEMA-356 Table 6-8 for nonconforming columns in flexure, then our damage assessment would indicate a 100% probability of exceeding the secondary Collapse Prevention (CP-S) for the first floor columns in the E-W direction. Based on this analysis, all columns in upper floors are within the Immediate Occupancy (IO) limit state.



Damage probability established using Tables contained in FEMA-356 for limit-states of nonductile concrete columns clearly identifies the first floor in the E-W direction as the zone of severe damage.

In summary, we illustrated the disadvantages of using design-based approaches as tools for automated post-earthquake damage assessment. In contrast, we demonstrated that the use of sensor data to estimate various relevant demand parameters and application of probabilistic measures can provide excellent real-time earthquake performance assessment results.

How Does REFLEXX Work?

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. 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.

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 highway, 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 also 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.

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

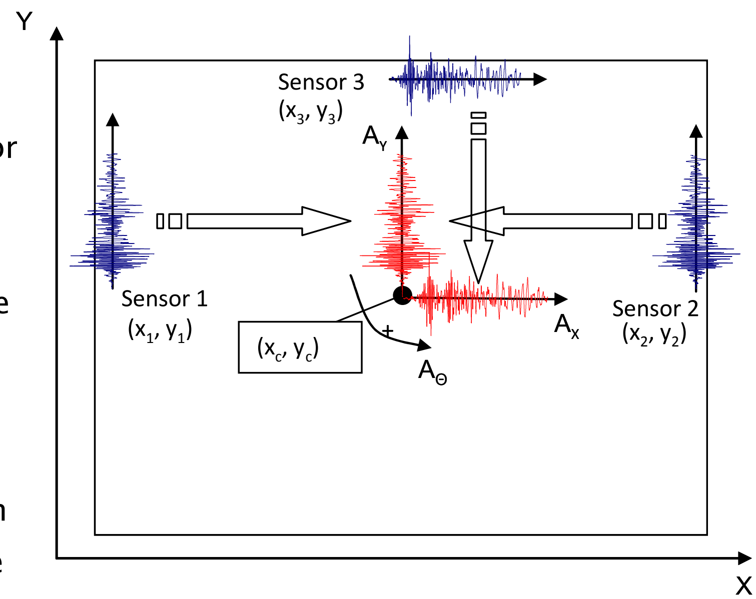
- Environmental sensors (temperature, wind speed and direction measurements).

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.

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 white paper we concentrate on distribution of accelerometers as they are the most commonly used sensors utilized in seismically instrumented buildings. Use of other types of sensors is highlighted in the Examples section of this document.

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 to the right.

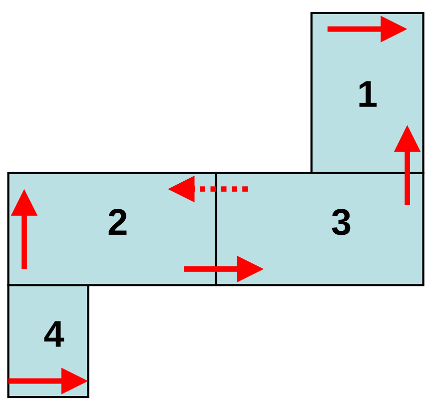


This floor has three sensors with the coordinates (x_1, y_1), (x_2, y_2) and (x_3, y_3). For every time step these sensors report displacements A_1, A_2 and A_3 in their respective directions. Let us assume that the floor's geometric center has coordinates (x_c, y_c). The relation between sensor displacements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

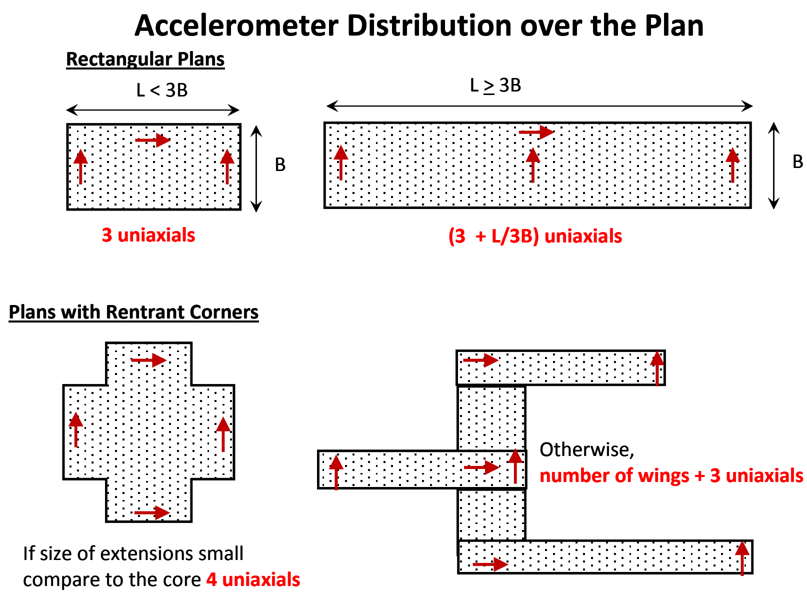


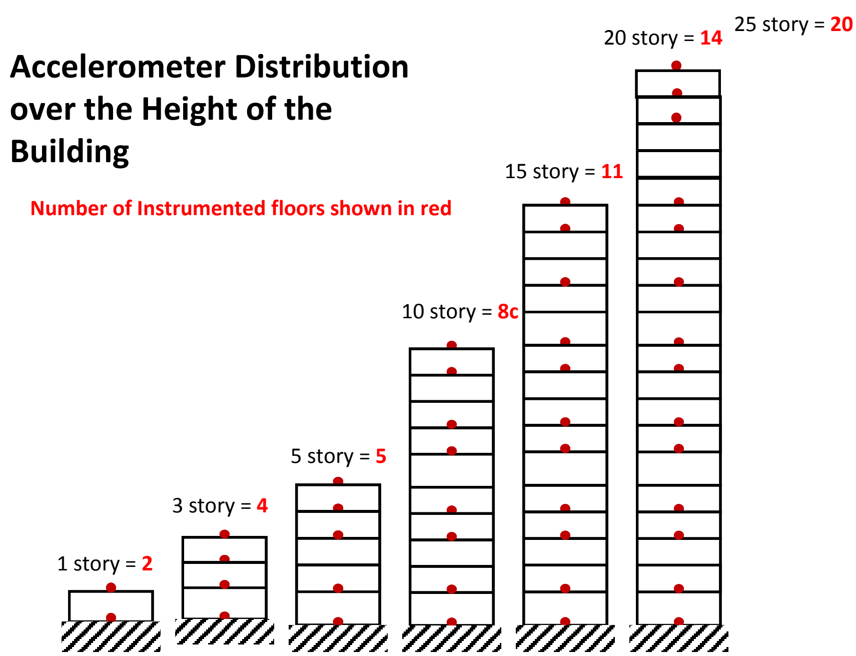
Using the above approach the motion at any point on the floor may be instantaneously calculated from the sensor data and as such the demand parameters for components of interest are calculated based on their specified location and orientation (if necessary).

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

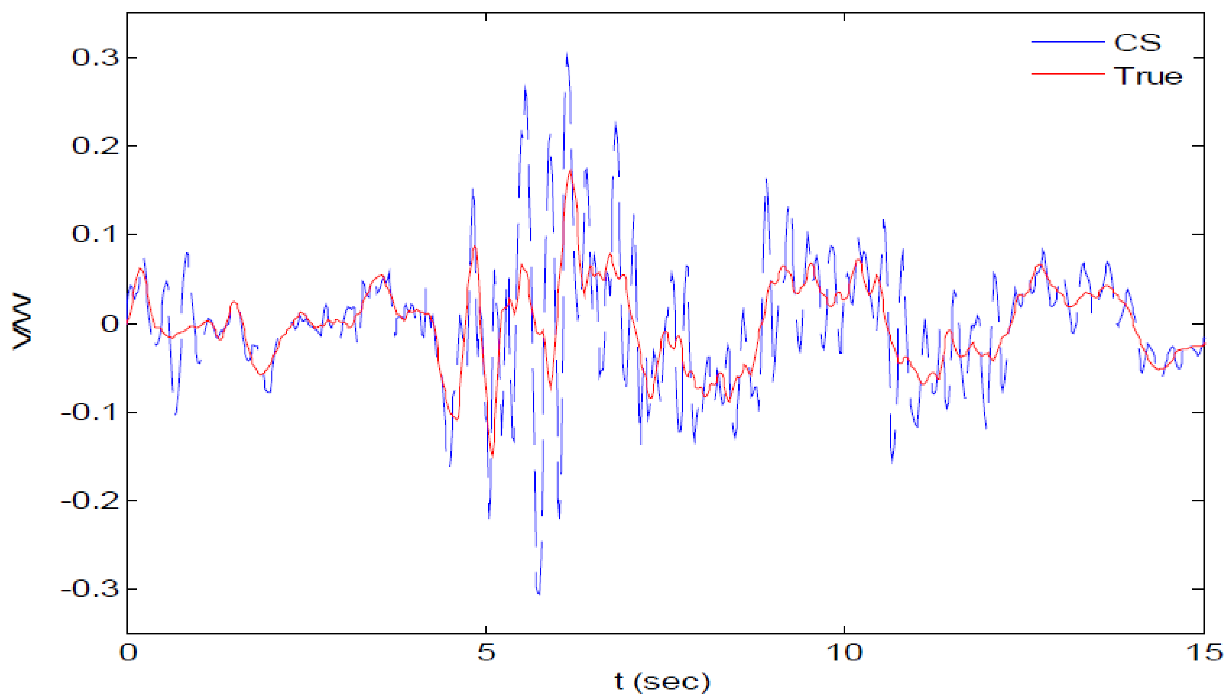
2005) and/or Observer schemes based on control theories (Bernal and Hernandez 2006) may be utilized to approximate the response of floors in between the instrumented floors.

Rough guidelines for deciding the number of sensors per instrumented floor and number of floors to instrument for a REFLEXX system implementation are provided in the following illustrations:



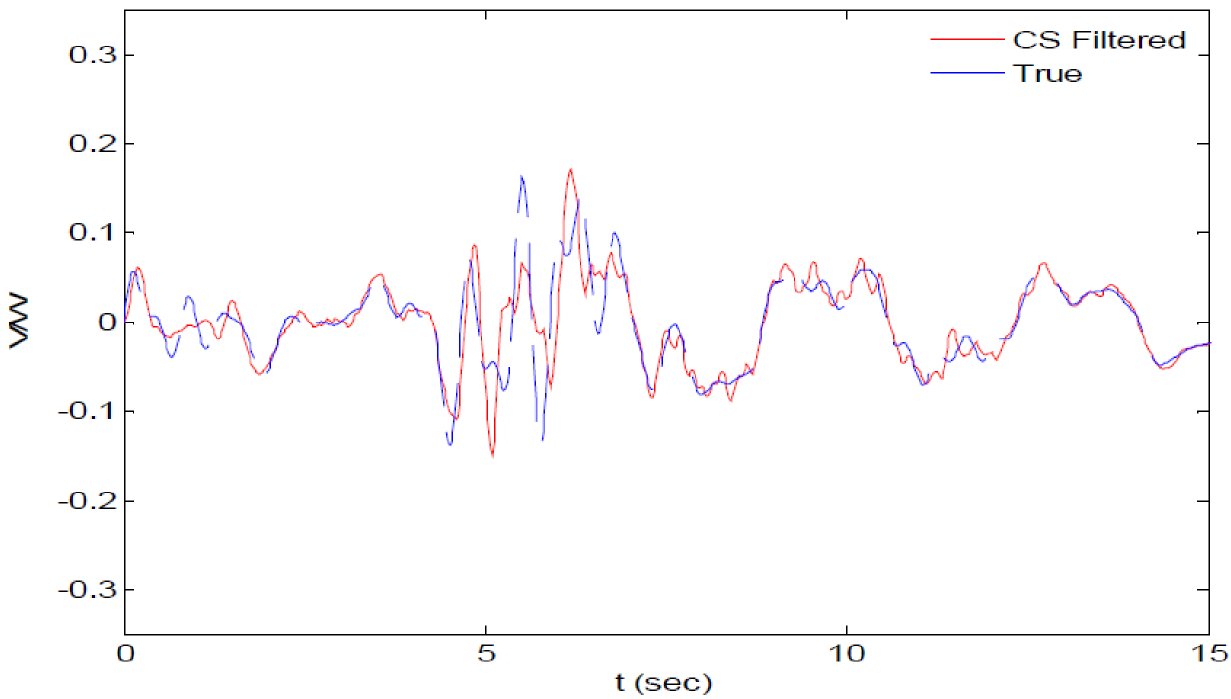


Bernal and Nasseri (2009) have documented the issues with simple interpolation techniques (linear, cubic spline, etc.) which may result in substantial overestimating of accelerations and forces if the number of floors instrumented are not sufficient to represent building vibration modes that have significant contributions to the total response of the building. As an example, they compared the cubic spline (CS) approximation of story shears to exact values for a 24 story building with sensors at levels 8 and 16 in addition to the base and the roof (see illustration below).



Comparison of the cubic spline estimates of base shear and the true values for the 24 story structure under Parkfield 2004 earthquake (from Bernal and Nasseri (2009).

They also demonstrated that by application of a low pass filter with a cutoff frequency at 3 Hz to the input motions (the frequency of the 5th mode which cannot be captured by sensor layout is 3.07Hz) much of the high frequency oscillations in story shear estimates can be eliminated resulting in acceptable post-filter results.



Comparison of the filtered cubic spline estimates base shear and the true values for the 24 story structure under Parkfield 2004 (from Bernal and Nasseri (2009).

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 uninstrumented 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.

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.

Deterministic Measures

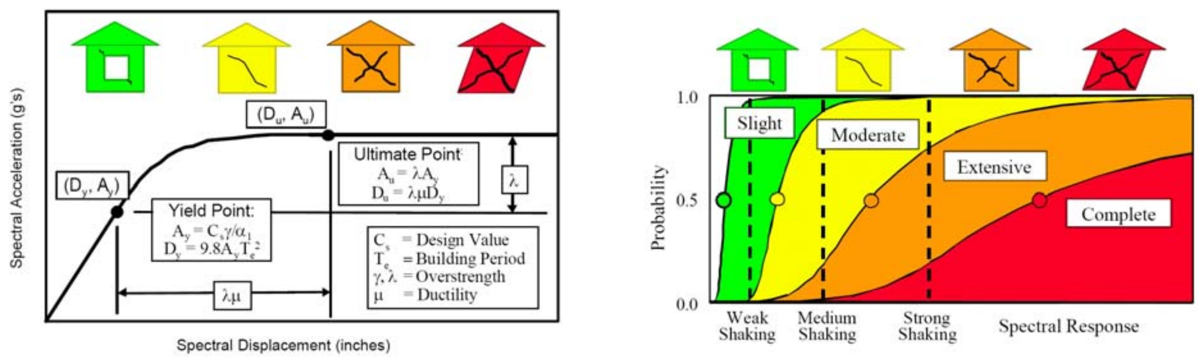
The issues related with the use of deterministic thresholds for damage detection and performance evaluation were discussed earlier in this document (see page 18). Deterministic thresholds, however, are useful in monitoring compliance with clearly established limits specified by design or performance 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 thresholds 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 thresholds 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 behavior 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.

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 nostructural 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).

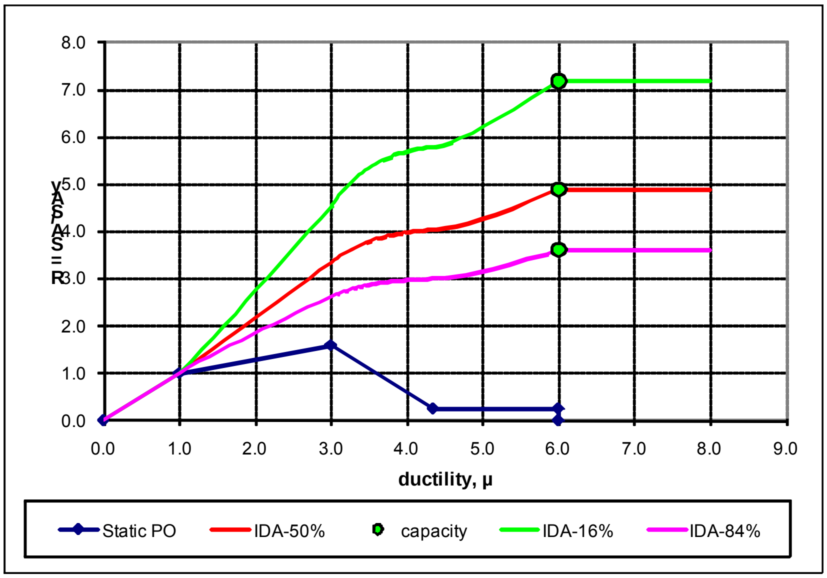


The Technical Manual for the HAZUS-MH Advanced Engineering Building Module (AEBM) provides a methodology for development of global fragility functions for building structural and nonstructural systems (FEMA-2003b).

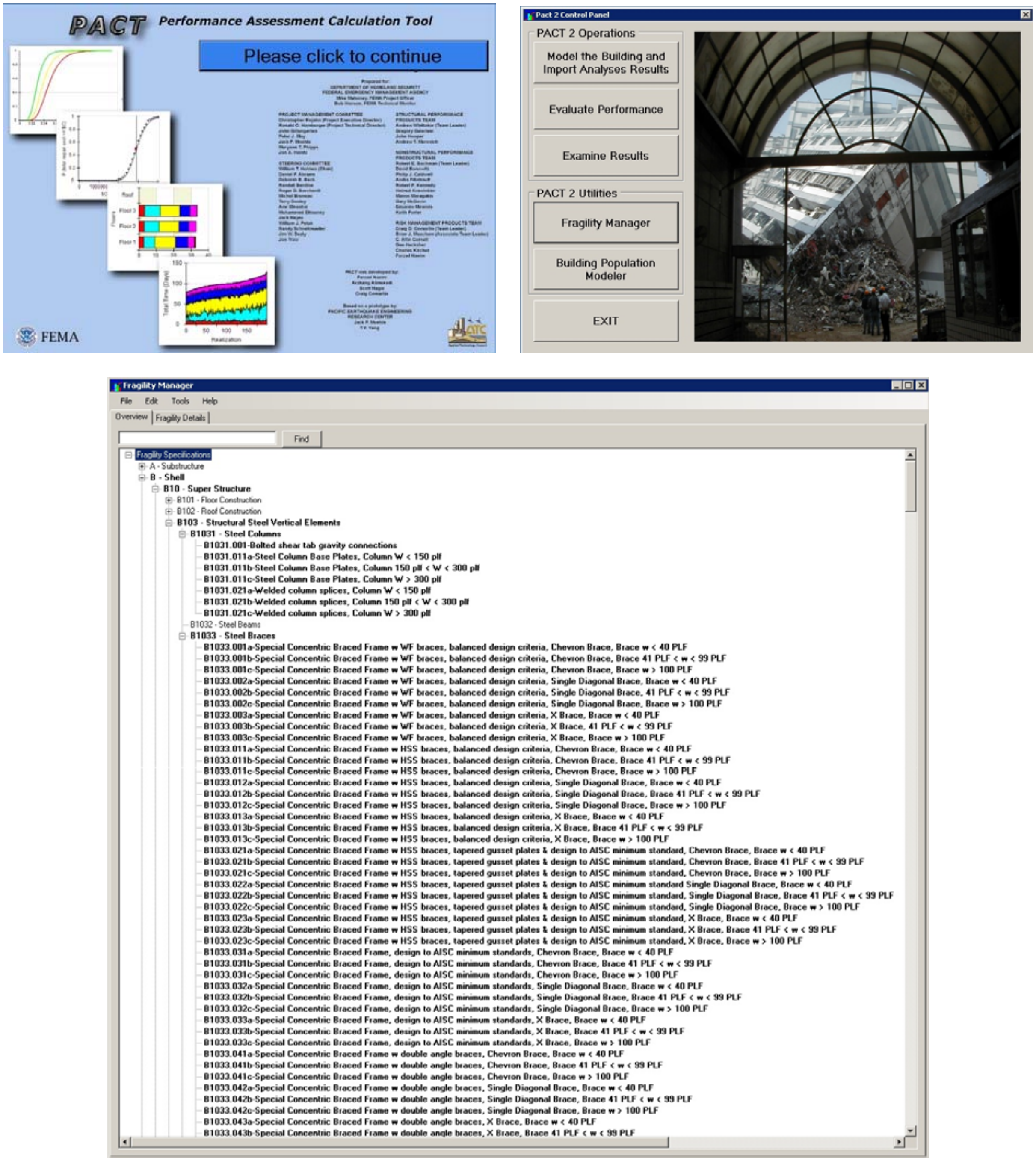
Other methods for establishing such fragility functions range from application of simple procedures based on pushover analyses such as SPO2IDA (Vamvatsikos and Cornell 2005) to a complicated series of linear or nonlinear analyses of the building.

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 (see for example publications by Miranda and his coauthors cited in the reference section of this document).

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 2.0 (Performance Assessment Calculation Tool Version 2) currently undergoing beta testing. 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 currently scheduled to occur sometime in 2011.



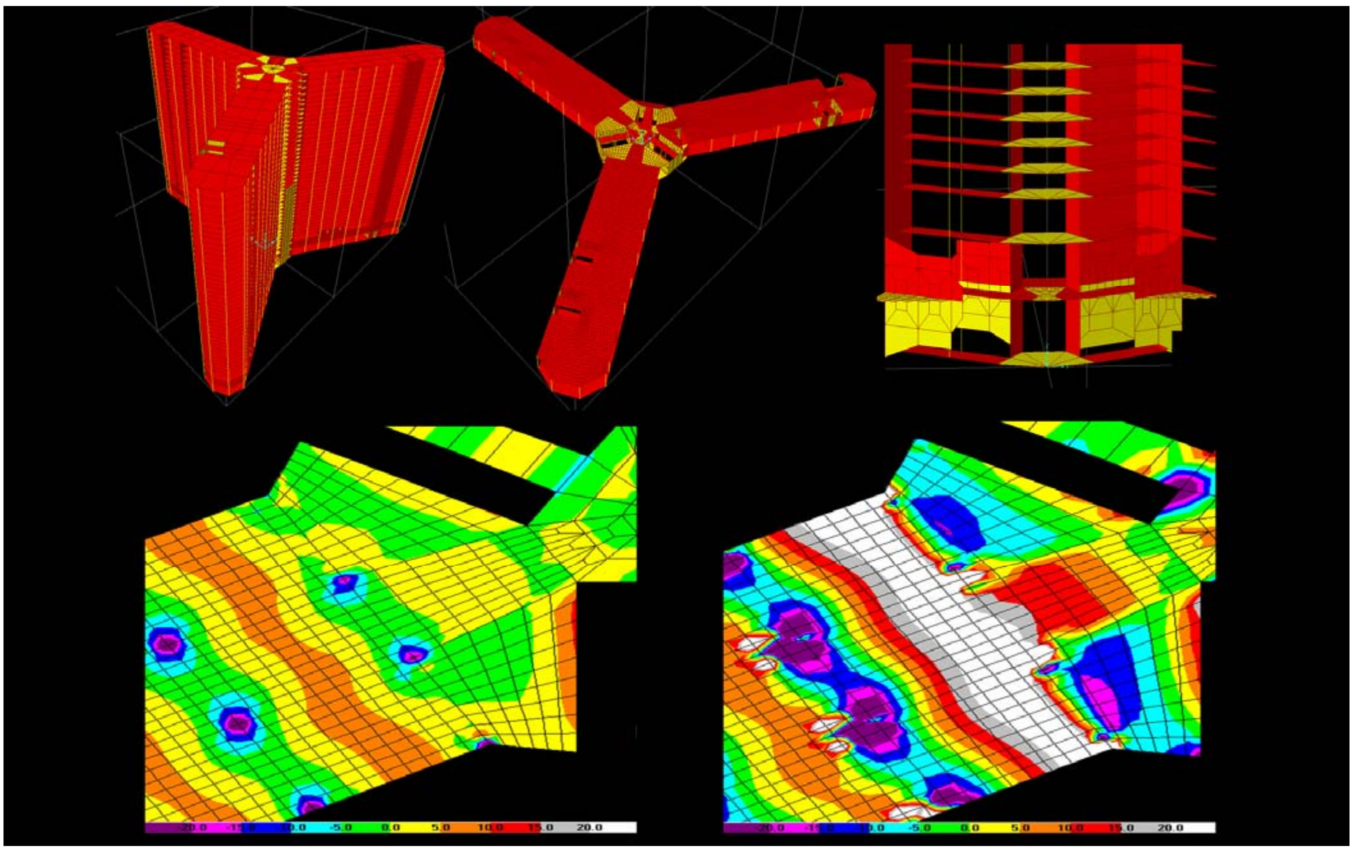
SPO2IDA software tool (Vamvatsikos and Cornell 2005) provides a direct connection between the Static Pushover (SPO) curve and the results of Incremental Dynamic Analysis (IDA), a computer-intensive procedure that offers thorough demand and capacity prediction capability by using a series of nonlinear dynamic analyses under a suitably scaled suite of ground motion records.



The ATC-58 Project and its software companion PACT 2 provide a wealth of component fragility specifications which may be readily imported and utilized in REFLEXX upon release by ATC.

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.



APPLICATION EXAMPLES

The following examples illustrate the utility and appeal of the real-time damage detection and performance evaluation system. While we emphasize various features of a DDPE system in one example or another, all or a selected subset of these features may be utilized for any building.

Example 1| Earthquake Damage Detection – Hospitals*

A six story hospital building equipped with real-time structural health monitoring and DDPE system experiences an earthquake. Within a few minutes after the earthquake the DDPE system obtains recorded floor accelerations and calculates other response entities necessary for evaluating building performance as shown in the table below and issues its performance report.

Photo from www.strongmotioncenter.org

Floor	Acceleration (g)	Velocity (in/sec)	Displacement (in)	Inter-story Drift (in)	Inter-story Drift Ratio
6	1.48	25.73	2.83	0.667	0.0036
5	1.32	22.31	2.50	0.458	0.0025
4	1.18	19.07	2.14	0.445	0.0024
3	1.06	16.19	1.71	0.605	0.0033
2	0.95	13.99	1.17	0.593	0.0029
1	0.83	8.28	0.79	0.791	0.0039

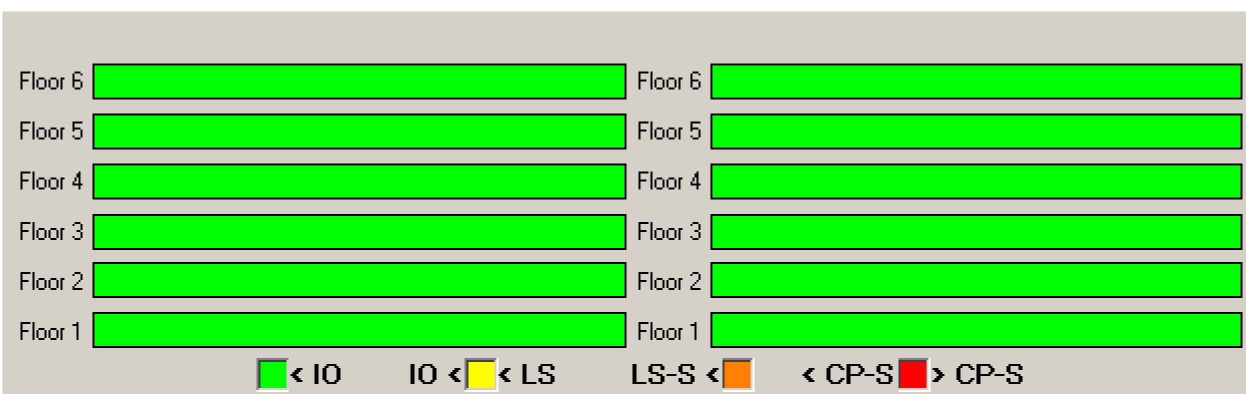
* Based on performance of Sylmar 6 Story Hospital during the 1994 Northridge Earthquake

The DDPE system for the building is configured to issue the following types of information in its report based on the threshold set by the structural engineer for the building at the time of DDPE setup for the building:

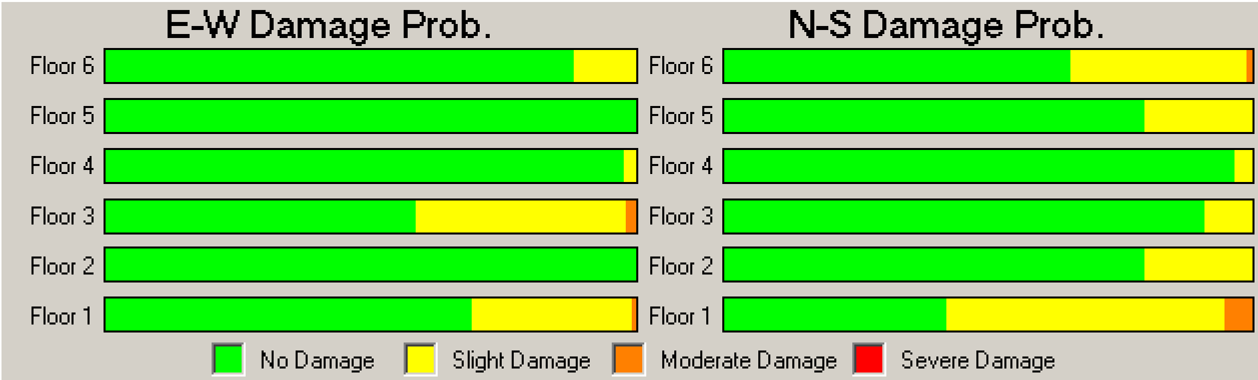
- Deterministic floor-by-floor structural system status per FEMA-356 Guideline or ASCE 41Standard.
- Probabilistic floor-by-floor structural and nonstructural system status based on HAZUS-MH Methodology
- Probabilistic component-by-component damage status and cost of repair estimate for the following components per ATC-58 fragility specifications:
    1. Exterior skin glass curtain wall
    2. Suspended ceilings on the first floor
    3. Unanchored file cabinets
    4. Desktop computers and copiers on the 3rd floor.

Contents of DDPE Report:

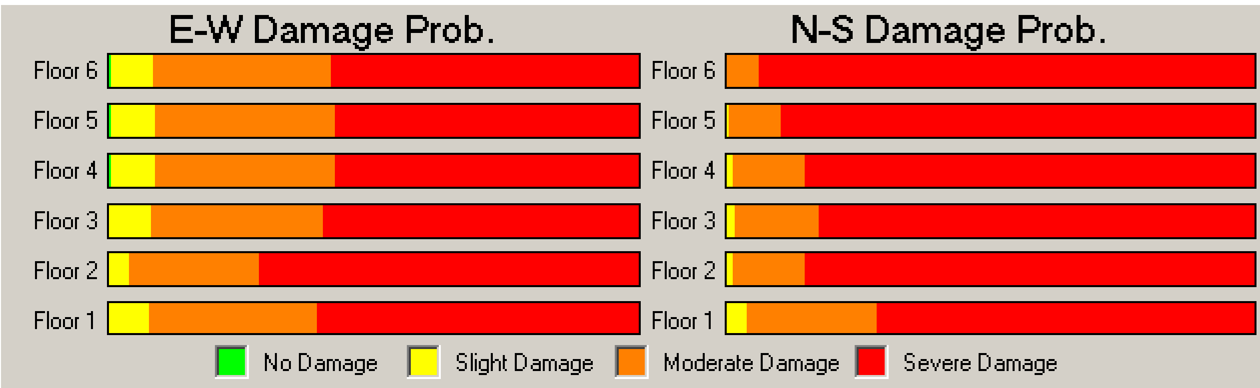
I. Deterministic floor-by-floor structural system status: Immediate Occupancy



II. Probabilistic floor-by-floor structural system status: No Damage to Slight Damage



III. Probabilistic floor-by-floor nonstructural system status: Moderate to Severe Damage



IV. Probabilistic component-by-component damage status

a. Exterior skin glass curtain wall: No Damage to Slight Damage

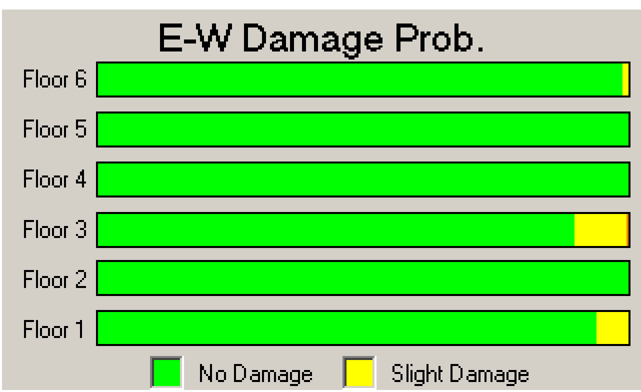


Photo from www.strongmotioncenter.org

b. Suspended Ceilings on the first floor:

Some tiles displaced or fallen (75% probability). Estimated cost of repair: $2.50 per square foot).

Significant tile falling and buckling of T-bars (15% probability). Estimated cost of repair: $22. per square foot).

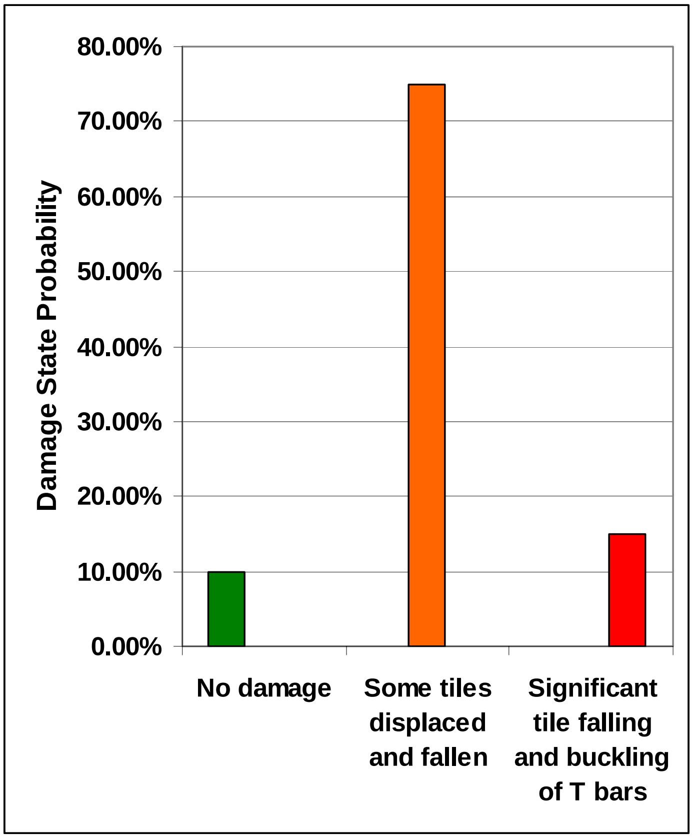
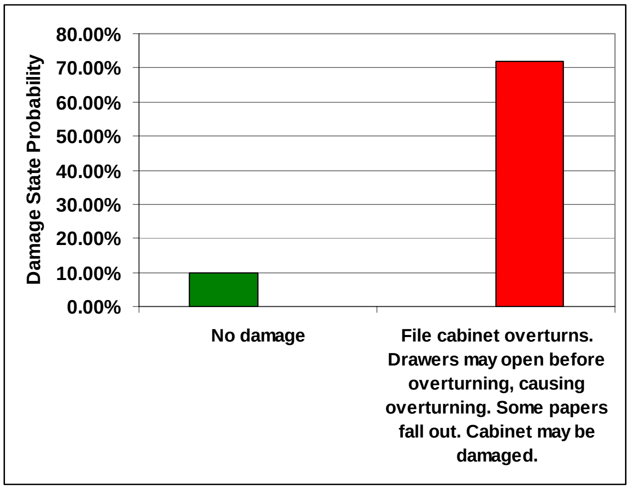
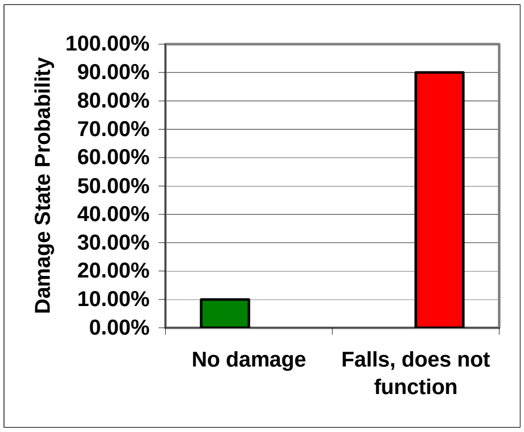


Photo from Naeim, F. (1997)

c. Unanchored file cabinets on the 6th floor: 72% of cabinets overturn. Estimated Cost of repair: $250 per damaged cabinet.



d. Unanchored Desktop computers and copiers on the ground floor: 90% probability of damage or not functioning.



Photos from Naeim, F. (1997)

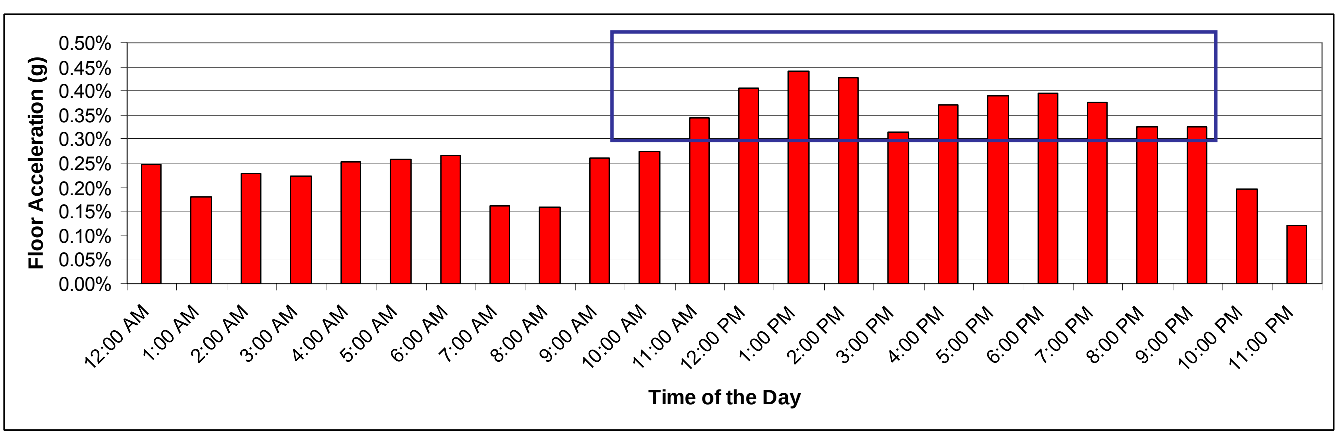
Example 2| Floor Vibration in Laboratories, Gymnasiums, Stadiums and Assembly Halls

This example illustrates several situations where real-time structural health monitoring and DDPE may be efficiently utilized to evaluate conformance of construction to specified or desired performance criteria established for proper functioning of equipment of comfort of inhabitants.

Case 1. Floor Vibration in a Laboratory

The design specifications for a laboratory floor calls for floor acceleration due to human walking not to exceed 0.3%g. The DDPE system has been configured to sample floor acceleration every 30 minutes during the working hours and at anytime the 0.3%g threshold is exceeded and generate and automatically issue daily, weekly, and monthly reports of floor performance.

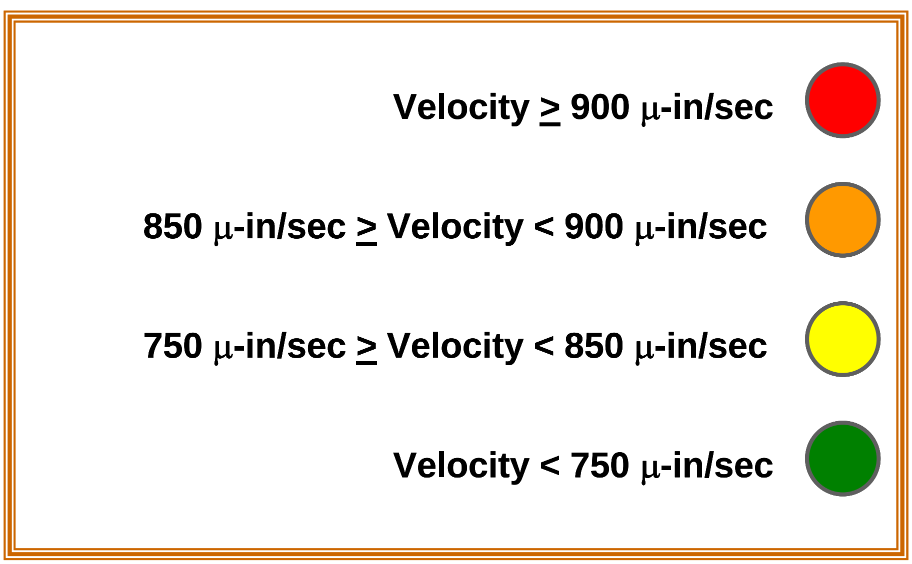
If performance as measured and reported is not satisfactory, rehabilitation measures can be implemented and success or failure of the rehabilitation measures can be objectively assessed via the already implemented DDPE system.



Case 2. Vibration in a Function-Critical Surgery Room

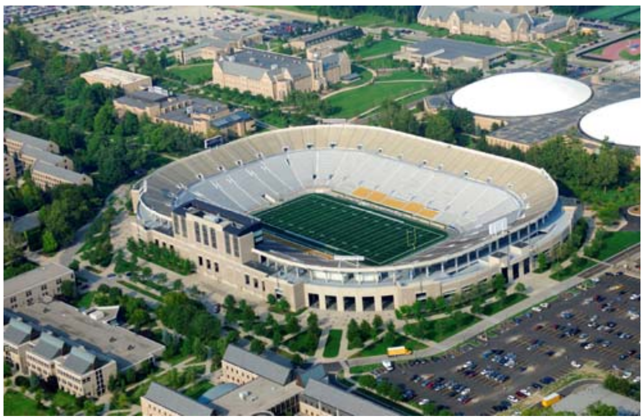
A hospital operating room set aside for Micro surgery, eye surgery and neurosurgery containing bench microscopes at magnification greater than 400x was designed according to AISC Guideline 11(AISC 2003). According to this criteria, the amplitude of vibration in the room should not exceed 1,000 micro-inches per second.

The real-time structural monitoring system for the room is configured so that the vibration status of the room is displayed real-time on an LCD display or laptop computer. A traffic light metaphor is implemented for conveying information on the LCD display. In order to allow a comfortable margin of safety for operations. The following setup for the various traffic light colors are established and an audible sound will be produced whenever the level of vibration is close to or exceeds the value corresponding to the red alert level.

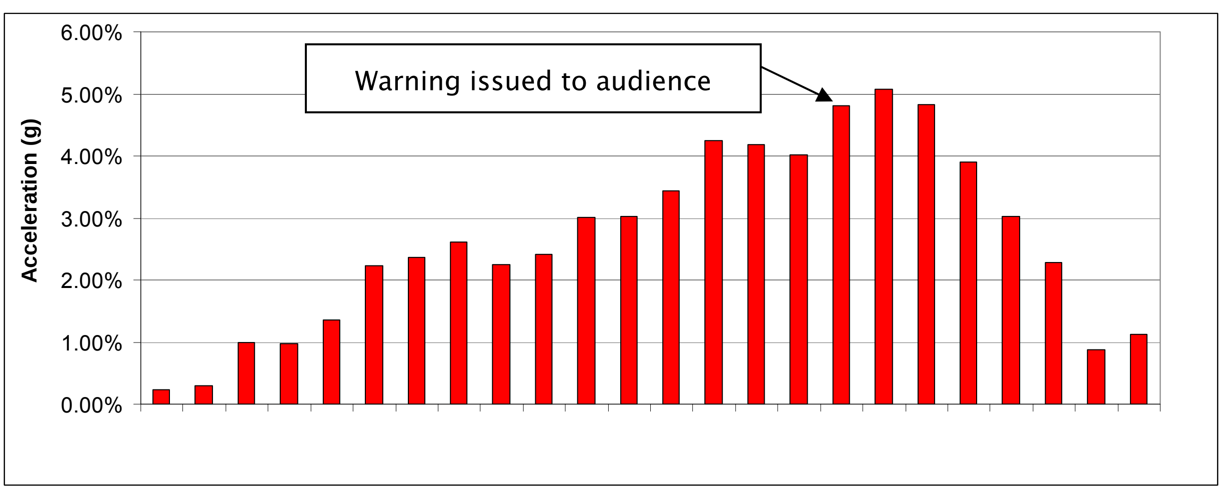


Case 3. Vibration due to Audience Participation in a Sports or Concert Facilities

Stadiums, sports arenas, and concert facilities face a catch 22 problem with respect to floor vibration induced by the audience. On the one hand they want the audience to be engaged by making noise and jumping up and down and on the other hand they need to control the amplitude of vibrations caused by the audience to an acceptable level.



To control the vibrations induced by participants, one such facility has established the policy of limiting the acceleration induced by human participation to the AISC Guideline 11(AISC 2003) limit of 5.00%g. The real-time structural health monitoring system for the facility may be configured so that the vibration level is graphically displayed on An LCD monitor or a laptop computer located at the control room similar to the one described in Case 2 so that the audience can be encouraged to slow down when the threshold is about to be exceeded.



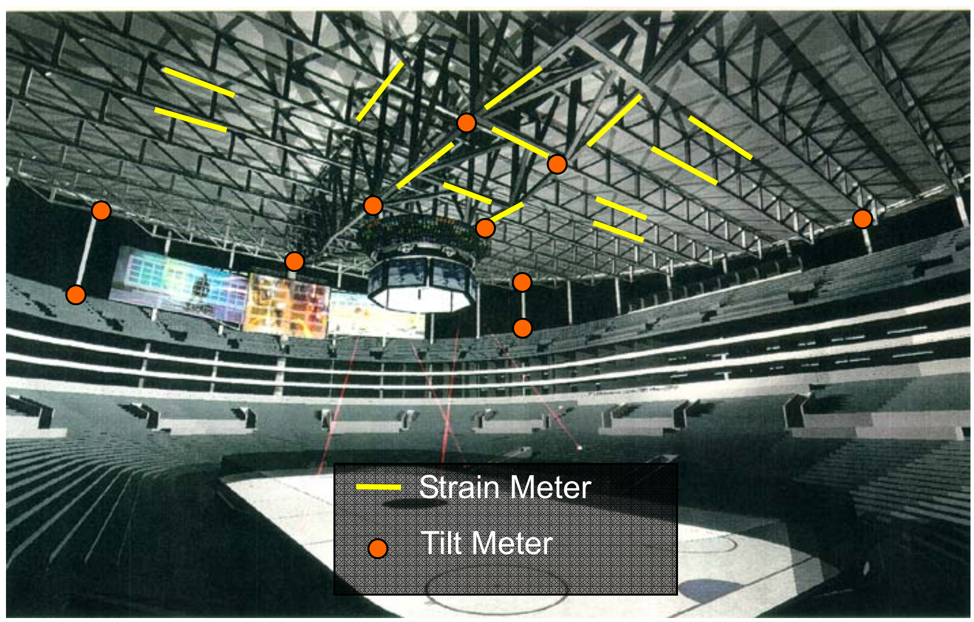
Example 3| Arena and Long-Span Roof Displacements and Stresses

Arenas, long-span structures and covered stadia host a large number of people and therefore their safety and functionality is of paramount importance. It is also very common to use these types of facilities to host large concerts where it is desired to hang heavy speakers and audio-visual equipment from the roof.

From www.TechBlog.com

Proper installation and use of real-time health monitoring system along with the DDPE system will allow the engineers and facility managers to assess the status of the roof instantaneously and make decisions with respect to modifications such as hanging heavy objects from the roof.

For example, strain meters may be installed on various locations of roof trusses to assess the existing and additional strains and stresses on the roof structure. Tilt meters may be installed in strategic locations to measure the relative displacement of various parts of the roof and to confirm the veracity of the information obtained from the strain meters. Real-time structural health monitoring and DDPE systems may be configured to display the relevant information on an LCD monitor or a laptop or send such information via e-mail to authorized parties as the evaluation or modification of the roof is ongoing. This enables the decision makers to assess and modify their decisions accordingly.

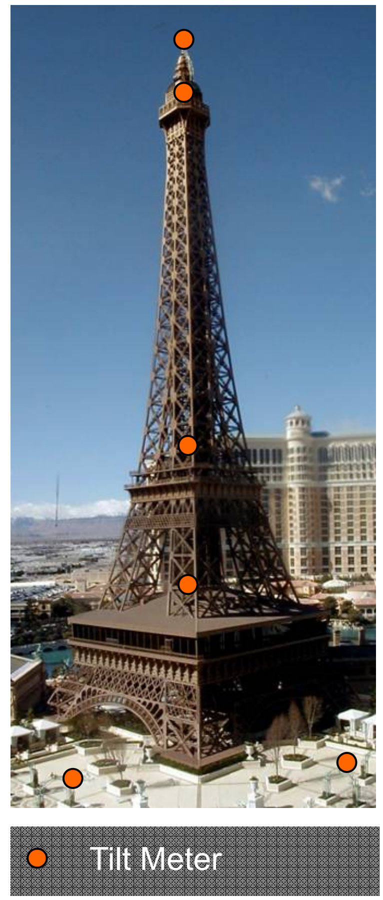


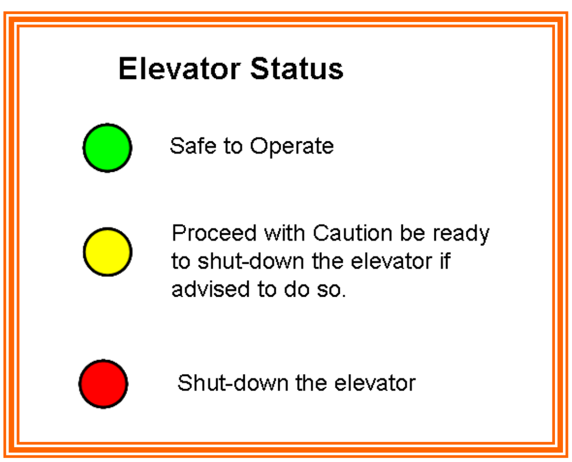
Example 4| Operability of observation Deck of a Tower or Elevators of Tall Buildings

During severe windstorms operation of elevators in towers or tall buildings may be unsafe because the relative displacement along the elevator shaft may cause the elevator cabin to get stuck in the shaft.

Knowing the tolerances of the elevator shaft and cabin for safe operation, the real-time structural health monitoring and DDPE systems may be configured to provide operation safety guidance to the operators of the elevators or communicate such information to the elevator system itself.

This can be achieved by installing a number of tilt meters along the height of elevator shaft to continuously measure and report the degree of out of plumpness of the shaft and recommend proper course of action.





Example 5| Earthquake Damage Detection – Tall Buildings*

A 52 story building equipped with real-time structural health monitoring and DDPE system experiences an earthquake. Within a few minutes after the earthquake DDPE system obtains recorded floor accelerations and calculates other response entities necessary for evaluating building performance.

From www.strongmotioncenter.org

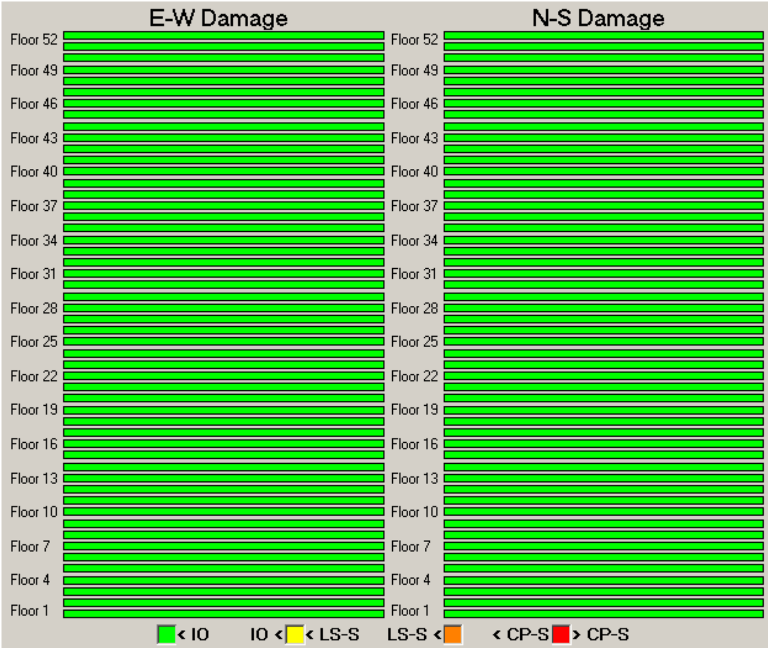
The DDPE system for the building is configured to issue the following types of information in its report based on the threshold set by the structural engineer for the building at the time of DDPE setup for the building:

- Deterministic floor-by-floor structural system status per FEMA-356 Guideline or ASCE 41Standard.
- Probabilistic floor-by-floor structural and system status based on HAZUS-MH Methodology
- Probabilistic floor-by-floor nonstructural drywall partition status per an engineer defined fragility function

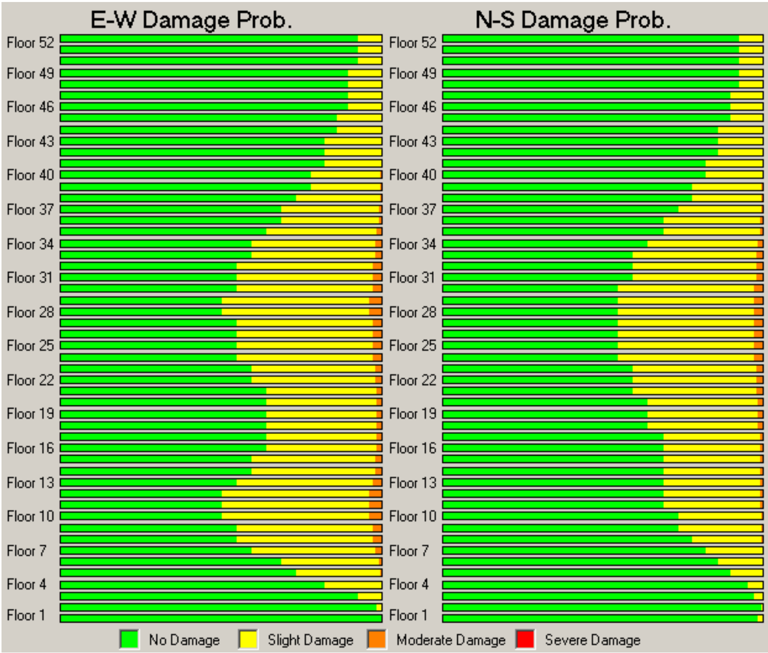
* A hypothetical example based on data extracted and modified from CSMIP-3DV and JAMA-ADA software system

Contents of DDPE Report:

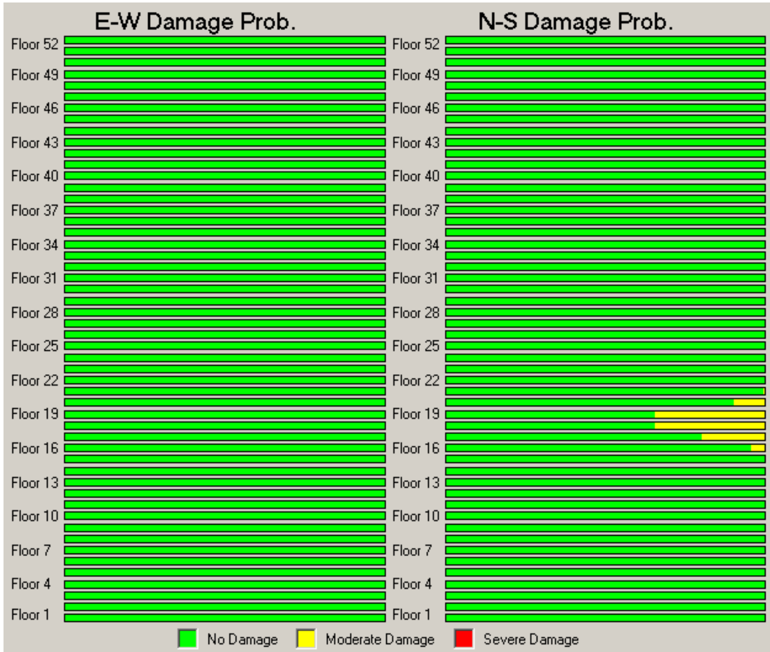
I. Deterministic floor-by-floor structural system status: Immediate Occupancy



II. Probabilistic floor-by-floor structural system status: No Damage to Slight Damage



III. Probabilistic floor-by-floor status of dry walls: Up to 40% chance of moderate dry wall damage in floors 18 and 19 in the N-S direction.



Example 6| Performance Evaluation of Hotels and Office Buildings

This example demonstrates the utility of real-time structural health monitoring and DDPE system in identifying and distinguishing various levels of damage in a building*.

The DDPE system for this 20-story hotel building is configured to issue the following types of information in its report based on the threshold set by the structural engineer for the building at the time of DDPE setup for the building:

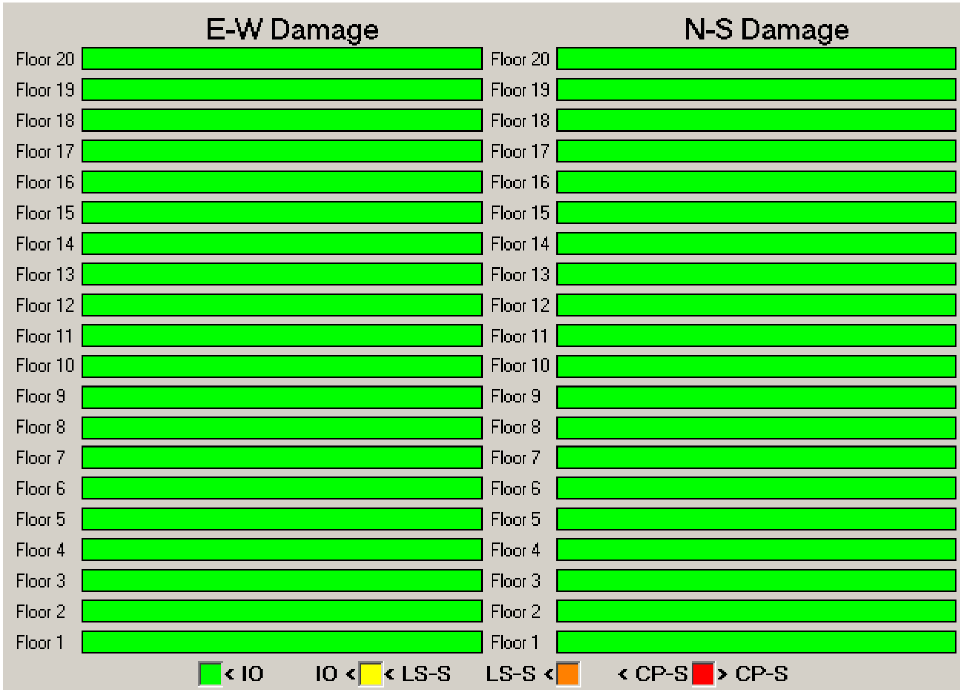
From www.strongmotioncenter.org

- Deterministic floor-by-floor structural system status per FEMA-356 Guideline or ASCE 41Standard.
- Probabilistic floor-by-floor structural and nonstructural status based on HAZUS-MH Methodology
- Probabilistic component-by-component nonstructural status for selected items per an engineer defined fragility specifications

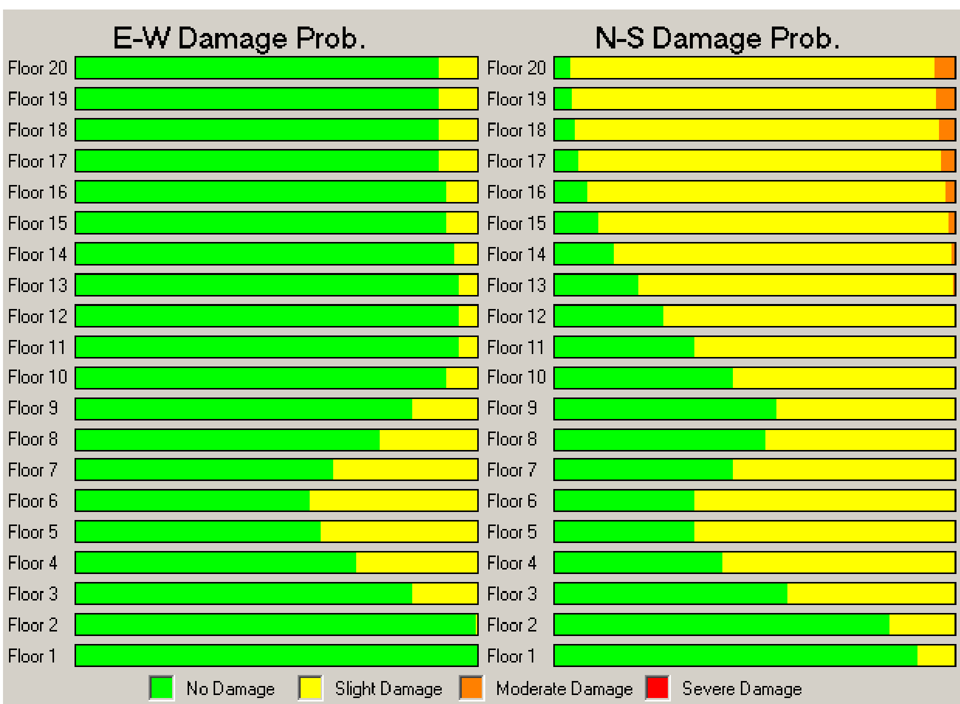
Within a few minutes after the earthquake DDPE system obtains recorded floor accelerations and calculates other response entities necessary for evaluating building performance and issues its performance report.

* Based on the performance of the 20 Story North Hollywood Hotel during the 1994 Northridge earthquake.

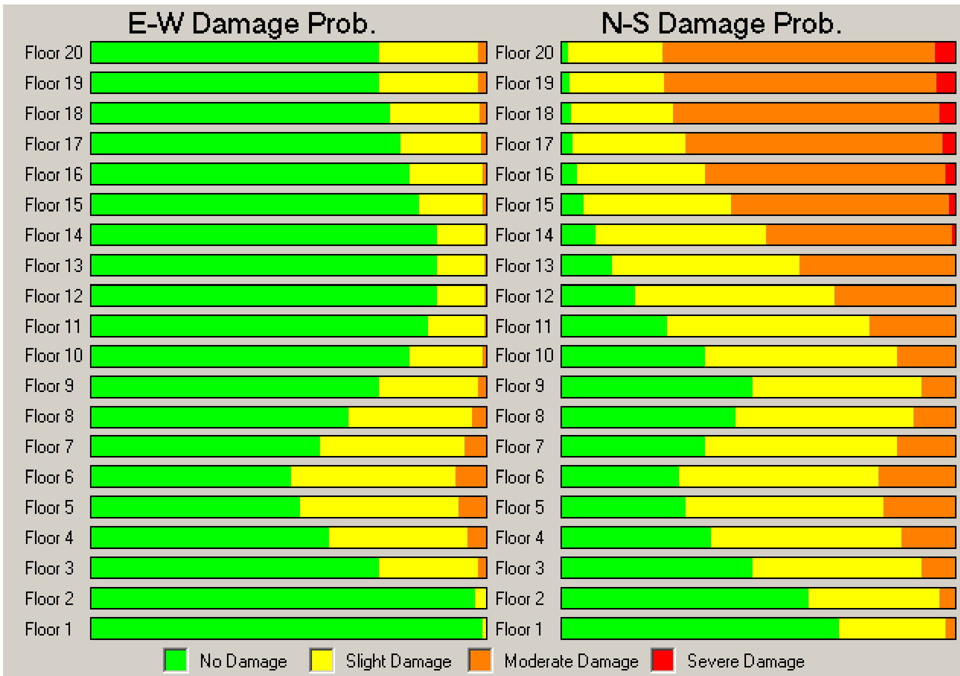
I. Deterministic floor-by-floor structural system status: Immediate Occupancy



II. Probabilistic floor-by-floor structural system status: No Damage to Slight Damage; damage more likely in the N-S direction.

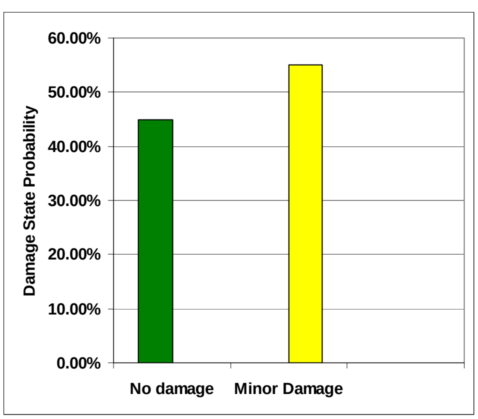


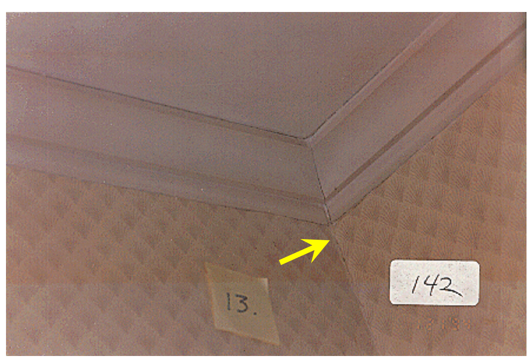
III. Probabilistic floor-by-floor nonstructural system status: No Damage to Moderate damage; damage more severe in the N-S direction and in upper floors.

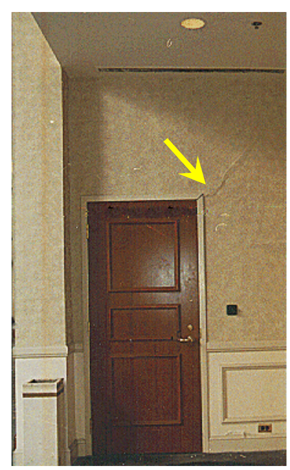


IV. Probabilistic component-by component status for selected items:

a. First Floor Dry Walls: No Damage to Minor Damage







Photos from Naeim, F. (1997)

b. Suspended Ceiling at Penthouse Kitchen: Major Damage

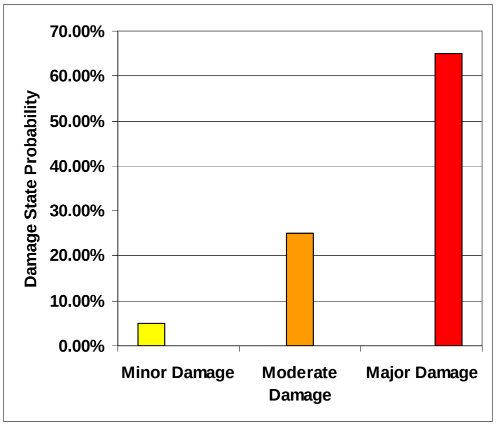


Photo from Naeim, F. (1997)

c. Sprinkler Heads on the First Floor: Minor Damage

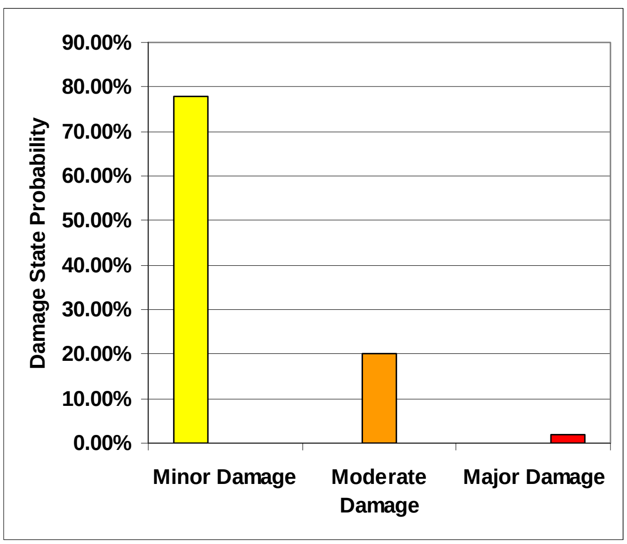
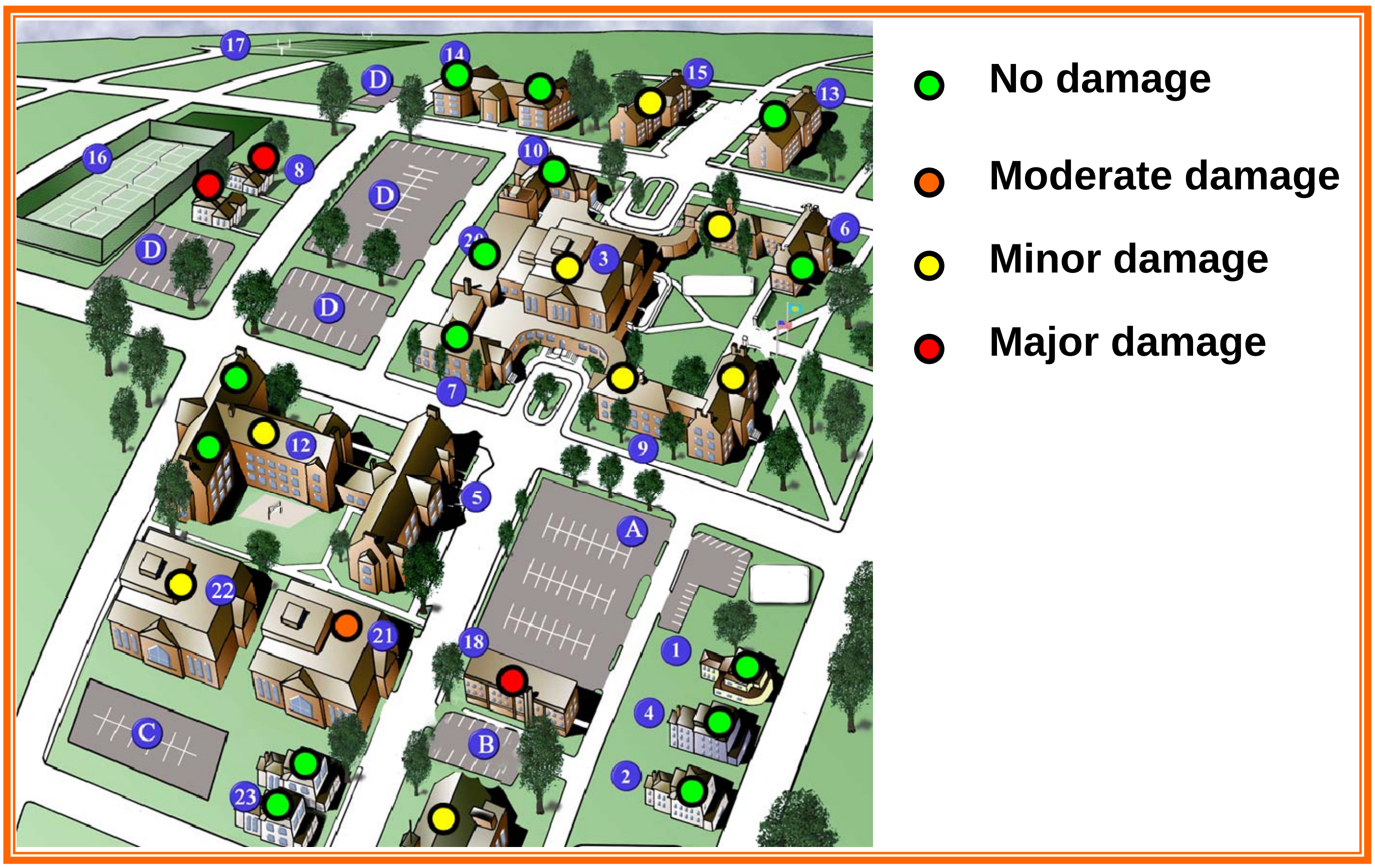


Photo from Naeim, F. (1997)

Example 7| Damage Detection and Performance Evaluation for Building Inventories and Campuses

Real-time structural health monitoring and DDPE systems may be configured to assemble, display and produce reports similar to the ones presented for previous examples for groups of buildings located in one general area such as university or manufacturing campuses or portfolios of buildings dispersed all over the world.

The results may be displayed within minutes of a triggering event in a summary format like the one shown below where by clicking the colored circle more detailed information is presented on the screen regarding the selected building. The DDPE system may also be configured to issue and dispatch detailed reports on selected buildings automatically once a triggering event occurs.



CONCLUSIONS

This White 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 White Paper satisfies these requirements in a very efficient and economical manner.

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