# Recent Experience from Buildings Equipped with Seismic Monitoring Systems for Enhanced Post-Earthquake Inspection

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**SUMMARY**
Several forward-thinking jurisdictions and large-facility administrations have established post-earthquake response programs (e.g., BORP – Building Occupancy Resumption Program) that permit the building's "engineer-on-call" to be pre-deputized to perform ATC-20 tagging in lieu of official inspectors. Seismic monitoring is a natural fit to these programs since engineers are assigned to a building in advance and thus are already familiar with the building and its structural characteristics. Consequently, several buildings were recently equipped with permanent seismic monitoring systems as part of an enhanced post-earthquake assessment service offered by leading engineering consulting companies. The systems utilize real-time monitoring and alerting based on user-selectable thresholds of critical response quantities such as peak interstory drift. The information is continuously, immediately and remotely available to onsite building and consulting personnel. This paper aims to share the technical, commercial, and implementation insights acquired by the technology provider and consultants by presenting cases studies of buildings with online-operational-lives spanning 4-to-6 years.

*Keywords: Seismic Monitoring, Post-Earthquake Inspection, ATC-20, Interstory-Drift*

## 1. INTRODUCTION

Occupants in essential facilities such as hospitals, emergency operations centers, strategic military installations, critical financial institutions, and nuclear power plants, cannot easily evacuate immediately after an earthquake and wait for a detailed safety assessment to reoccupy the facility and resume operations. Hospitals and medical facilities, in particular, have a profound need to maintain building operational status and function in the aftermath of strong earthquakes to allow continued care for current patients and also to receive new patients injured by the disaster (Wilson et al, 2004). A proactive solution to performing rapid, detailed, and accurate post-disaster safety evaluations of these facilities is needed.

Post-earthquake safety standards and response programs not only benefit building owners and municipality officials, they help to create new and proactive solutions for performing rapid and accurate post-disaster safety evaluations. San Francisco, for example, and several other forward-thinking jurisdictions established Building Occupancy Resumption Programs (BORP) that permit the building's "engineer-on-call" to be pre-deputized to perform ATC-20, *Postearthquake Building Safety Evaluation Procedures*, (1989) Red/Yellow/Green building tagging in lieu of official inspectors (BORP 2001). The US Navy independently developed a similar innovative Rapid Evaluation and Assessment Program (REAP) for their west coast hospitals and medical facilities (Swanson 2011). The common goal among these programs is to formalize and pre-organize the post-earthquake inspection process.

Traditional visual-based post-earthquake inspections can impose high costs and inconvenience on building owners and occupants alike. For example, physical access to structural members usually requires the removal of non-structural components such as interior partitions and fire proofing. The post-earthquake detailed inspection requirements of welded steel moment frame buildings with pre-Northridge Earthquake style connections can be especially time consuming and costly to implement. Prolonging expensive downtime, limited resources such as qualified inspectors may not be immediately available after a damaging event, especially for dense urban areas.

Beginning in 2006, several buildings along the US west coast were equipped with permanent seismic monitoring systems as part of an enhanced post-earthquake assessment and inspection service offered to building owners from leading engineering consulting companies, Figure 1.1. The primary goal of these systems is to provide useful information to the post-earthquake inspection and recovery process, supplementing the traditional visual-based inspection process in terms of both speed and quality.


**Figure 1.1.** Seismic Monitoring Systems recently installed by the Authors

An overview of seismic monitoring systems is provided in the following section followed by a discussion regarding integration monitoring systems with post-earthquake response programs. Several case studies of buildings with online-operational-lives spanning 4-to-6 years are then presented. Finally, lessons learned from these and other similar projects are summarized.

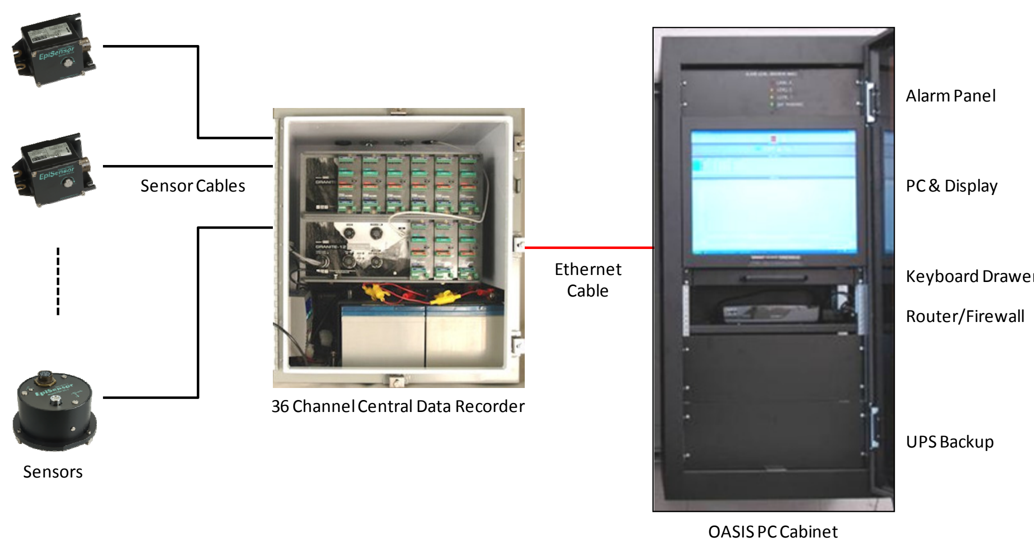


**Figure 2.1.** Kinemetrics OASIS Seismic Monitoring System

## 2. SEISMIC MONITORING SYSTEM OVERVIEW

The seismic monitoring system described here is the OASIS system from Kinemetrics, Inc., Figure 2.1. The OASIS (On-line Alerting of Structural Integrity and Safety) system is a flexible structural monitoring system that provides for the collection and processing of real-time acceleration, velocity, displacement, and inter-story drift data. The OASIS seismic monitoring system consists of three major hardware subsystems; sensors, data acquisition system, and the PC display and alarm system.

Accelerometers are the sensor of choice due to their robustness and ease of installation. Because interstory drift is the critical response quantity of interest, and no sensor exists to-date that can reliably capture story displacements (Skolnik, 2012), double numerical integration is performed on the real-time data. This difficult process requires several processes such as linear band-pass filtering (Fig. 2.2) and is one of the primary functions of the OASIS software.

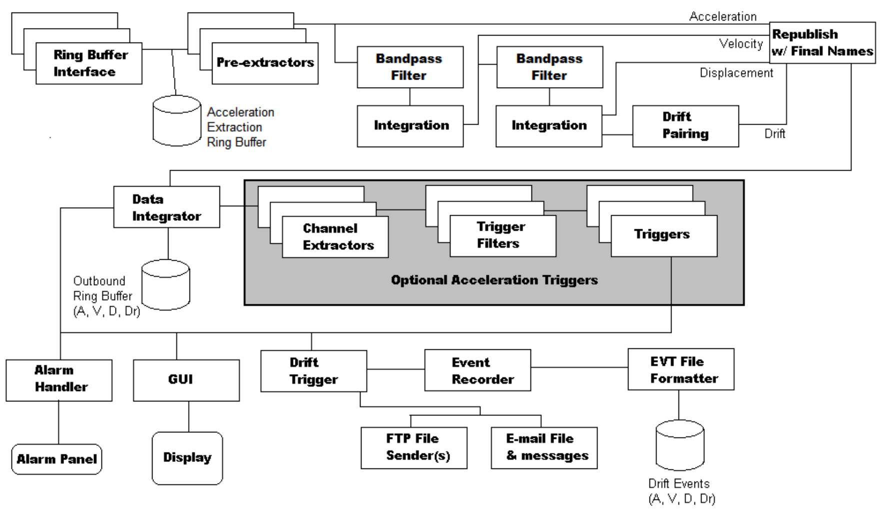


**Figure 2.2.** Data Flow in the OASIS processing.

Central data recorders, as opposed to multiple distributed recorders, remain the only viable solution for robust long-term systems. Although running long analog sensor cables can be expensive, current wireless technology for timing and power, although promising, are not yet mature enough for such demanding applications. The central recording unit provides the necessary tools for continuous real-time and event-driven data acquisition such as precise GPS-based timing, power supply and management, signal processing, analog-to-digital conversion, and data file formatting and storage. It also provides the necessary communication interfaces for the PC display and alarm system.

The OASIS PC cabinet consists of a rack-mounted industrial computer and display with Alarm panel, Cisco router/firewall and UPS backup power. OASIS software running on the PC is responsible for controlling the Alarm Panel, performing real-time processes (e.g., double numerical integration), and providing interactive display for user control. A host of notification methods (i.e., email, ftp, sms, etc.) are available per user discretion. Figure 2.2 below illustrates the data flow through the OASIS program.

### 2.1. Seismic System Integration

A key aspect in the successful enhancement of post-earthquake response service is the integration of the seismic monitoring system within the overall process. Post-event response can be divided into three phases; immediate response, inspection phase, and detailed evaluation. Although different tools are required for the different phases, the information provided by a seismic monitoring system can be useful during all three.

The immediate response phase refers to the onsite response action immediately after the shaking and the "dust settles". The natural inclination of most occupants is to immediately evacuate a building following a major earthquake. Avoiding unnecessary evacuations is critical especially for essential facilities such as hospitals, acute care medical facilities, emergency operations centers, strategic military installations, nuclear power plants, and prisons and detention centers. Occupants of these facilities cannot easily evacuate immediately after an earthquake and wait for a detailed safety assessment to reoccupy the facility and resume operations. Therefore, the goal with respect to immediate response is more about enabling continued occupancy and operation, and less about triggering an evacuation as is often thought to be the case. The OASIS system alarms and notifications provide confidence to building operation personnel that it is OK to recommend occupants stay inside and continue "business as-usual" or commence emergency response/cleanup operations. It is also important to note that onsite building operation personnel may trigger an evacuation for reasons other than structural damage. Damage to contents or building systems may prevent continued operation of the facility, and so onsite personnel require occupancy evaluation guidance that is broader than just the information from structural monitoring systems.

The post-earthquake inspection phase occurs as soon as possible but can be up to a few days to weeks depending on the extent of regional damage and the contractual arrangement between the facility and inspecting engineers. Event information from the OASIS system can be used to aid inspecting engineers in the inspection and tagging process. For example, specific floors that exceeded thresholds can be initially targeted for inspection. More detailed building response data may be provided using post-processing tools and the results presented in a brief report or handout to supplement the immediate information provided by the OASIS system. This quantitative information is an invaluable supplement to the usual post-earthquake inspection process, which is based predominately on visual indicators of damage. This is especially the case in modern buildings with cladding and interior systems that prevent access to the underlying structure. In these cases the level of structural damage must be inferred from damage to non-structural systems, which is dependent on particulars such as the quality of detailing etc., and therefore highly variable. The quantitative data provided by the monitoring system helps inspecting engineers reach less conservative conclusions regarding the acceptability of the subject building for continued occupancy.

Lastly, the detailed evaluation and recovery phase can extend over a period of months. Main event and the inevitable aftershock data can aid in the subsequent engineering evaluation in assessing potential damage, need and priority of any structural system inspections, and extent of required repairs. This is particularly applicable for pre-Northridge steel moment-resisting frames which are susceptible to fracture of the welded beam-column connections in strong ground shaking. This damage was first detected in the 1994 Northridge, California earthquake, and is relatively difficult to detect and expensive to repair. The FEMA-352 (2000) document; *Recommended Postearthquake Evaluation and Repair Criteria for Welded Steel Moment-Frame Buildings*, requires inspection of a random percentage of connections for all buildings of this type that experience shaking in excess of a specified threshold level. These guidelines are likely to be adopted by local jurisdictions following a significant earthquake and the data from these systems may be submitted to justify a reduced inspection program where appropriate. The City of San Francisco Department of Building Inspection's Building Occupancy Resumption Program includes the following text in Section D.5 of the required program format: "*[Optional] Placement of accelerometers. Instrumentation is recommended as part of an Emergency Inspection Program for all highrise buildings in San Francisco. Correct placement of accelerometers can provide valuable post-earthquake information about the performance of a building. This option may be considered in certain cases as a means of reducing the percentage of joints required to be inspected after an earthquake.*"

Regardless of structural system type, having quantitative data on the seismic/structural performance of a building that is to undergo detailed engineering evaluation, or repair/strengthening design, is invaluable to a practicing engineer. Computer models of the building can be calibrated against actual performance increasing the confidence of the predictive analysis regarding performance of the repaired or strengthened building in future earthquakes.

## 3. CASE STUDYS

### 3.1. Critical Financial Institutions

Downtime of critical financial institutions can be extremely costly to the tenant institution and its customers. One company with its headquarters in Downtown San Francisco has opted to minimize its potential downtime by implementing an enhanced BORP compliant program with seismic monitoring system. As part of this project, two separate buildings were instrumented; one consisting of a 31 channel system, the other with a 42 channel system. The larger system is installed in a building with two structures seismically isolated by an expansion joint. Although separate data acquisition systems are used for each structure, all data and results are available and displayed in single OASIS PC.

This particular system recently captured responses to two small earthquakes of M4.0 and M3.8 with epicentres near Berkeley approximately 10 miles away on October 20, 2011. Figure 3.1 displays example data from the event files provided immediately by the OASIS system.

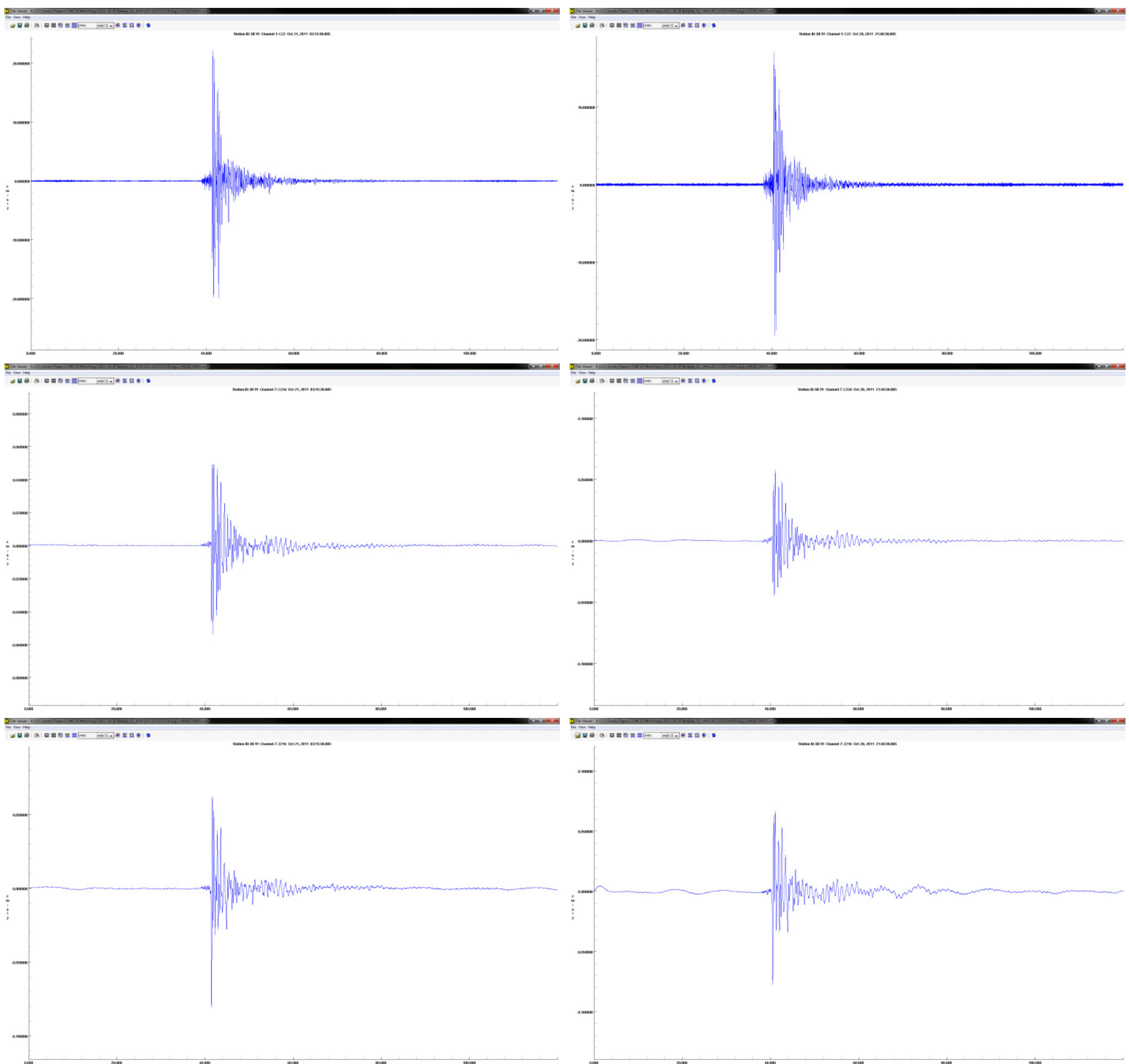

**Figure 3.1.** Sample data from one sensor during M4.0 (left column) and M3.8 (right column) earthquakes on October 20, 2011 near Berkeley, CA. Top, middle and bottom rows display acceleration (cm/s$^2$), displacement (cm), and interstory drift (cm) versus time.

As shown in Figure 2.2, the OASIS program applies several band pass filters during the integration process to correct for baseline transients, among other things, that result in spurious long-period drifts in integrated data (e.g., velocity, displacement, and interstory drift). However, it has been documented that optimal filtering parameters maybe signal dependent (Skolnik, 2010). This can be observed in bottom row of Figure 3.1 which shows the interstory drift obtained with the same set of sensors but for the two different earthquakes. Note the suspect long period responses are more prevalent in the second event (bottom-right) than in first event (bottom-left). Unfortunately, it is not possible to apply an event-customized filtering scheme in real time. However, it does not apparently affect the peak interstory drift value, which is the most important result for rapid post-event inspection. Furthermore, the filtering approach can be easily optimized post-processing for the subsequent reports used for the "detailed evaluation and recovery phase" described in section 2.1.

Being one of the first of its kind, several practical lessons were learned from this particular system. For example, shortly after the installation, a small earthquake shook the building and the recorded data displayed excessive unrealistic interstory drift values. It turns out that some sensors were wired incorrectly and had inverted polarity. Because of this event, minor errors such as there were discovered and corrected accordingly. Having tests that can check system performance beyond functionality is understandably of critical importance. Another somewhat related lesson is that long-term maintenance contracts have proved essential in maximizing system uptime and catching potential issues in a timely manner. The fact of reality is that technical issues may occur. However, having proper maintenance programs in place allow users to catch and resolve any issues prior to potential events. Another notable lesson is what to do when the tenant's lease expires and plan to move to another building. In this case, there may be some disagreement in who exactly owns the system. In other words, is it part of the building infrastructure? Although the tenant may have paid for the system and its installation, the building owner may perceive it to be a building specific system and take ownership. The lesson here is simple; have rights to ownership language included in relevant lease agreements.

### 3.2. CALTRANS District 4 Headquarters

Degenkolb Engineers designed a seismic retrofit scheme for this 15 story steel moment-resisting frame constructed in 1991 and located in Oakland, California, Figure 3.3. The building is the headquarters for Caltrans District 4 and houses the Transportation Management Center for the San Francisco Bay Area. Previous testing indicated that the welded connections were vulnerable to fracture, and consequently the building presented a risk to life safety in the event of a major earthquake.

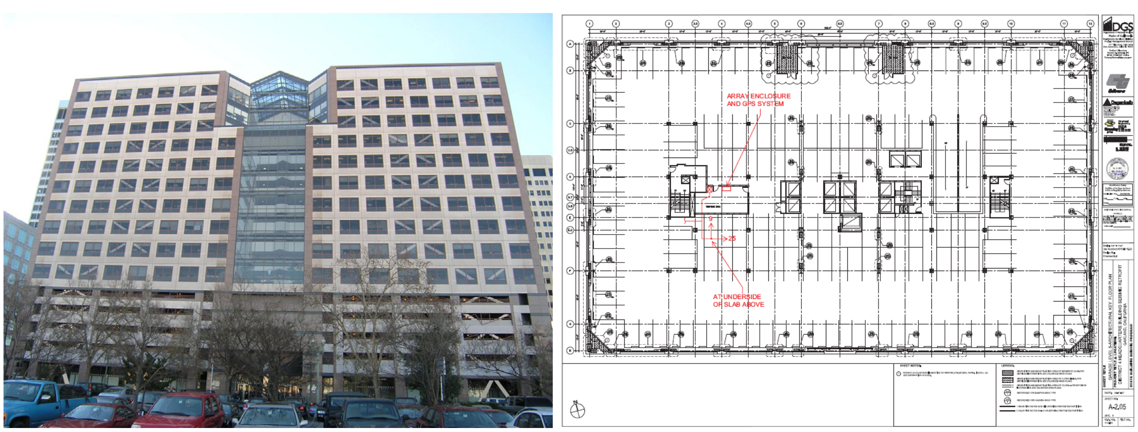


**Figure 3.3.** Caltrans District 4 Headquarters (left) and sample plan (right) showing sensor layout

After considering several retrofitting schemes, one that included strengthening some existing connections and adding viscous dampers was selected. To meet the seismic performance requirements of the State of California, Department of General Services this scheme reduced interstory drifts to

1.8% in a 475-year return period event. Non-linear time history analyses were performed to verify the performance of the retrofitted structure. Full scale connection testing and detailed finite element analyses were also performed to verify the deformation capacity of the proposed retrofit details. The extra steps taken beyond typical engineering practices were intended to provide better assurance that the project's performance goals would be met during the design basis seismic event.

As part of the project, Caltrans elected to install a 36 channel seismic monitoring system to provide improved post-earthquake inspection and recovery process for the reasons presented in Section 2.1. The system includes an onsite OASIS monitoring system, and is remotely monitored in real-time by Degenkolb Engineers from both the nearby Oakland office and the Portland, Oregon office. This increases the likelihood that event data from the building can be evaluated shortly after an event while inspecting engineers are in transit to the building.

**Table 3.1.** Alarm Drift Thresholds and Actions

| Drift | Description | Action |
|---|---|---|
| 0.1% | Noticeable building movement | Perform remote evaluation using data from the system |
| 0.5% | Minimum expected threshold for some fracture of the remaining unretrofitted pre-Northridge connections | In conjunction with other triggers or communication with building, activate the engineering inspection of the building |
| 2.0% | Minimum expected threshold for damage to the primary lateral system | Same as above. Evacuation is not triggered automatically but may occur after remote review of data and communication between onsite personnel and inspecting engineers |

The monitoring system is an integral part of the post-earthquake response process that includes provision for the three phases of response described in Section 2.1. As part of this process Degenkolb Engineers is contracted to monitor the system, and for post-earthquake building inspection. A comprehensive post-earthquake inspection manual was developed which integrates the monitoring system into the overall response process.

Results from the analysis performed as part of the retrofit project were used to set the drift performance limits. The alarms are intended to provide direction on what floors have experienced the highest levels of demand. The overall alarm level for the building will be triggered if three or more drift measurements are above the alarm thresholds described in Table 3.1.

### 3.3. US NAVY Hospitals and Medical Centers

As early as 2002, the US Navy developed and deployed building-specific post-earthquake evaluation plans utilizing seismic instrumentation to facilitate rapid and accurate post-earthquake evaluations of several of their essential medical facilities (Wilson et al, 2004). Since then this program has evolved in to the Rapid Evaluation and Assessment Program (REAP). This program utilizes facility-specific inspection criteria and seismic monitoring systems to provide occupants of these essential facilities post-disaster inspection tools that can be used to perform fast, accurate and detailed building safety evaluations. Combining the principals of Performance-Based Earthquake Engineering (PBEE), known drift limit states of various building materials and structural systems, and the Post-Earthquake Safety Evaluations of Buildings (ATC-20) standard of care, the REAP utilizes a Seismic Monitoring System (SMS) to help facility managers quickly and accurately evaluate the post-disaster safety of these important facilities. This innovative post-disaster safety assessment program has been deployed at the three of the US Navy's west coast-based healthcare facilities: Naval Hospital Bremerton (NHB), Naval Medical Center San Diego (NMCSD), and Naval Hospital Twentynine Palms (NHTP), (Swanson et al, 2011). NMCSD is the world's largest military medical facility.

As part of their design of seismic upgrades to the 6-story, 1.2 million square-foot NMCSD facility, Reid Middleton developed and deployed the REAP and SMS for this essential facility. The SMS consists of an initial phase of 36 channels of real-time seismic monitoring with a full build out of 60 channels when the program is fully deployed. The Kinemetrics OASIS system was utilized in this project. The REAP makes use of the SMS to measure earthquake performance of the facility and provide real-time feedback to the post-disaster inspection team. REAP inspection tools also include annotated facility drawings, checklists, maps, photography, and related inspection information to allow the safety assessment teams to quickly and accurately examine the structure for post-disaster occupancy. The REAP SMS connects to and deploys building seismic performance data to the USGS Advanced National Seismic System (ANSS) Network. See Figure 3.4 for the NMCSD SMS Master Plan.

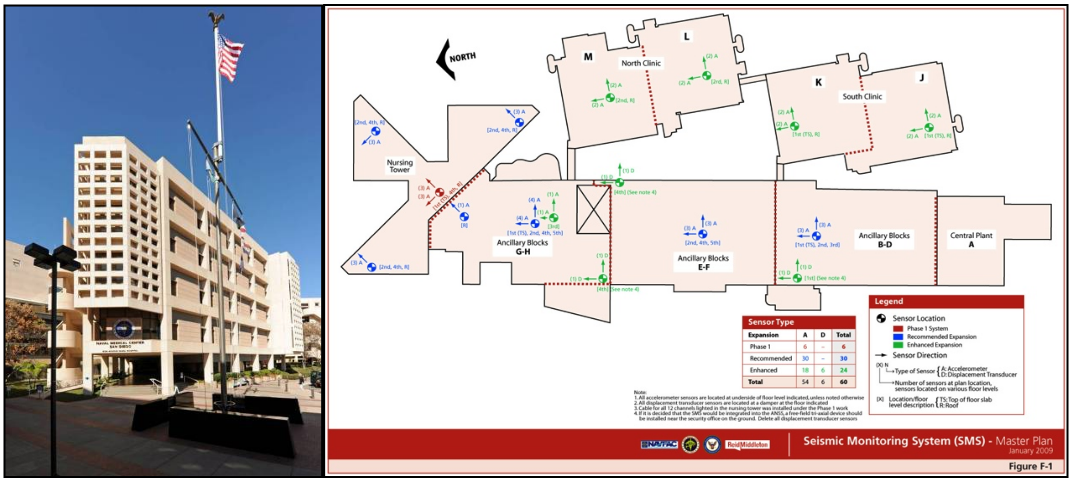


**Figure 3.4.** Naval Medical Center San Diego (left) and the SMS master plan (right) showing sensor layout

Not long after the initial phase of the NMCSD REAP and SMS were deployed, the monitoring system captured structural responses to the M7.2 Mexicali earthquake that occurred on Sunday April 4, 2010. The building site is approximately 200km away from the event epicentre and as a result, no post-earthquake building evaluations were performed, however, the SMS did record small building movements in the nursing towers. This information was made available to the facility management personnel to assemble in an overall building assessment report that was furnished to NMCSD management.

Table 3.2 below shows how sensitive the SMS is and presents the measured absolute accelerations and calculated drift values for all floors of the 6-story nursing tower structure. Note that values at floors without instrumentation are obtained by linear interpolation.

**Table 3.2.** Calculate Response Quantities

| Floor | Height (ft) | Abs Acc (g) | | Abs Vel (in/s) | | Abs Disp (in) | | Drift (%) | |
|---|---|---|---|---|---|---|---|---|---|
| | | NS | EW | NS | EW | NS | EW | NS | EW |
| 6 | 80.0 | 0.093 | 0.097 | 4.09 | 4.54 | 0.74 | 0.72 | 0.057 | 0.064 |
| 5 | 64.0 | 0.081 | 0.077 | 3.41 | 3.64 | 0.64 | 0.61 | 0.057 | 0.064 |
| 4 | 48.0 | 0.070 | 0.056 | 2.74 | 2.75 | 0.55 | 0.50 | 0.084 | 0.085 |
| 3 | 32.0 | 0.062 | 0.049 | 2.35 | 2.16 | 0.44 | 0.40 | 0.084 | 0.085 |
| 2 | 16.0 | 0.054 | 0.042 | 1.97 | 1.57 | 0.34 | 0.31 | 0.084 | 0.085 |
| 1 | 0 | 0.046 | 0.034 | 1.59 | 0.98 | 0.23 | 0.21 | - | - |

Beyond interstory drift, engineering quantities like response spectral accelerations at the base and XY particle motion at the roof are also items considered of interest as they allow for more accurate assessment of loads on building systems and components. Example results are displayed in Figure 3.5.

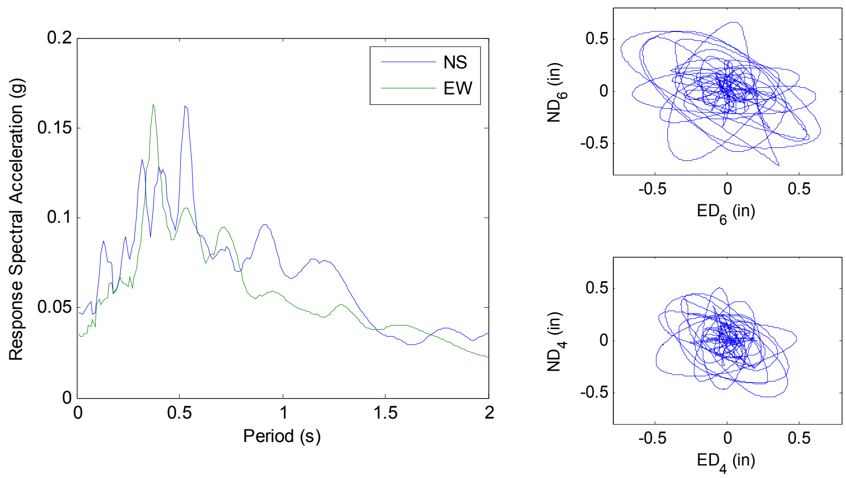


**Figure 3.5.** Response Spectral Accelerations from First Floor (left) and XY Particle Motion (right) where $ND_x$ and $ED_x$ are the $x^{th}$ floor North-South and East-West Displacement respectively

## 4. LESSONS LEARNED AND CONCLUSIONS

In this developing field of structural health monitoring, the case studies presented in this paper help to identify the various applications and benefits of this technology to specific buildings with specific needs. The following is a summary list of observations and lessons-learned from this innovative and important early work on applications of structural health monitoring for real-time post-earthquake evaluations of buildings.

1. It is easier to get funding for a building monitoring system as part of a larger retrofit (or new design) construction project than as a standalone activity.
2. Depending on the method of contracting used for the project, the engineering implementation cost can be a significant portion of the total cost of the system. The required tasks for the design professional may include some or all of the following:
   a. Preliminary system layout for budget estimates. Assistance with obtaining pricing estimates and with system selection.
   b. Detailed drawings and specifications for the selected system including electrical drawings.
   c. Review of system shop and implementation drawings and submittals.
   d. At least a partial presence during installation.
   e. Determining appropriate deformation trigger levels for the system. These may be adopted from a previously performed seismic assessment or retrofit design, or a project specific assessment of some type may be required.
   f. Determining exact as-installed coordinates of each sensor and associated information for illustrative and data processing purposes.
   g. Learning how to access, configure, and maintain the system.
   h. Configuring system parameters including automated email alerts, ftp-downloads, etc.
   i. Developing a post-earthquake inspection process that incorporates the monitoring system at each phase of response. This includes developing the inspection manual, running initial training and periodic updates for onsite personnel and inspecting engineers.
   j. Deciding on the appropriate method of detailed event data assessment and whether this is to be performed remotely or not.
   k. Ensuring that remote monitoring systems are operable and connected.
   l. Addressing inevitable problems with system performance, internet access, etc.
3. The cost of cabling does not usually present a significant cost compared to the cost of the hardware and other implementation costs. However, this may not be applicable where access is difficult or restricted, or where hazardous materials are present.
4. It is usually simpler to obtain a standalone DSL line for internet access than to attempt to utilize an

available interior building network for remote access and real-time streaming. Internal building network administrators are usually reluctant to provide access through firewalls etc.

5. While false positives are rare, and can be minimized by careful selection of triggers, they do happen. Care should be taken before implementing evacuations or other actions based on automatically generated system output, e.g. emails or panel displays. In general, conclusions from these systems should supplement observations by onsite personnel. This situation becomes less problematic if the primary goal of the system is considered to be enhancing the probability of continued occupancy, rather than automated damage detection and evacuation.
6. Real-time monitoring is most valuable onsite when hardwired to the base monitoring/recording system. Continuous remote offsite monitoring is most valuable as a means to ensure that the system is operational and healthy, and to improve the likelihood of the data being available outside the affected region after an earthquake.
7. Turnover of personnel on both the side of the inspecting/monitoring engineering firm and at the client building is an ongoing administrative cost that must be considered.
8. Setting deformation limits for these systems is less complex if the system goal is to enhance occupancy rather than to trigger evacuation. Conservative limits can be developed relatively easily with some knowledge of the building structural system and characteristics. Less conservative limits may then be possible with a more careful engineering evaluation of both the structure and non-structural systems.

Seismic monitoring systems, such as Kinemetrics OASIS system, address the immediate response portion of the overall post-earthquake response process. Software that is flexible and powerful allows qualified users to develop methods to monitor in real-time a wide variety of performance metrics. However, additional tools are necessary for more detailed evaluation of event data including ability to rapidly view and print demand parameters such acceleration, velocity and displacement traces, story drift and displacement responses, sensor response spectra, in a broad user-friendly report format.

Experiences gained through projects such as those presented as case studies here offer invaluable insight into what is required to implement a comprehensive three-phase response plan towards enhanced post-earthquake inspection and assessment. Ongoing collaborative efforts among leading technology providers and consulting engineers will lead to more lessons learned and continued rewarding results for their customers and the overall earthquake engineering community.

**AKCNOWLEDGEMENT**

The authors would like to acknowledge the building owners who kindly agreed to allow us to present this work despite unavoidable disclosure of certain information regarding their facilities.

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