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IMPROVING BUSINESS CONTINUITY FOR UAE BUILDINGS USING SHM AND PBEE-BASED RAPID EVALUATION

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Abstract

Hundreds, if not thousands, of buildings worldwide have been instrumented with strong-motion sensors for the sole purpose of cataloging structural response to damaging and potentially damaging earthquakes. Engineers and seismologists use these data to further our understanding of actual building dynamic behavior, ultimately leading to advancements in research and building code improvements. Over time, the cost-bearing public (owners and residents) indirectly benefit from this work by owning and residing in safer structures. However, there is also opportunity for the public to benefit directly from earthquake monitoring technology. Recent (and not so-recent) advances in client-based information-driven services has led to a new application; business continuity.

Although the concept of using strong-motion data to the benefit of building owners has been considered by engineers and seismologists, in the opinion of the authors, it has only recently been implemented as a holistic, commercially viable, business continuity solution. We attribute this to a combination of strategic academic and industrial partnerships, advantageous commercial opportunities, and a growing body of knowledge and experience on the topic. Therefore, this paper presents a real business continuity solution based on strong-motion monitoring, performance-based earthquake engineering (PBEE) principles, and standard-of-care for post-disaster safety assessments.

Occupants in essential facilities such as hospitals, strategic military installations, financial institutions, and ultra-tall buildings, cannot easily evacuate immediately after an earthquake or wait for a detailed safety assessment to reoccupy and resume operations. The decisions to evacuate and reoccupy are difficult, especially under a state of distress, and can have dire consequences if made incorrectly or too slowly (e.g. panic related injuries, significant loss due to unnecessary downtime, etc.). Examples of avoidable financial loss and injury ultimately due to uninformed decision making are easily found in across areas of low and high seismicity.

In UAE, for example, occupants in very tall buildings have endured long-duration swaying due to large distant earthquakes originating in southern Iran. Consequently, several UAE critical buildings were selected for Structural Health Monitoring (SHM) systems to alert on exceedance of structural safety performance thresholds, and implementation of rapid earthquake response planning, aimed to avoid unnecessary evacuation and shutdown and/or minimize expensive downtime. The real-time SHM systems provide intuitive onsite display, alerting, and remote notifications on exceedance of demand/design parameters such as interstory drift, absolute acceleration, and response spectra. This information, which is continuously, immediately and remotely available to building personnel, is useful throughout all phases of the post-earthquake response, including immediate evacuation decisions, emergency response, inspection procedures, and the damage rehabilitation and retrofit process. On an individual building level, this program improves safety and increases business continuity; however, on a public/societal level, these tools can increase the earthquake resiliency of our communities. Presented here is an overview of the rapid post-event assessment solution along with several cases studies.

Keywords: Business Continuity; Structural Health Monitoring; Earthquake Response Planning; ATC-20, PBEE

1. Introduction

Hundreds, if not thousands, of buildings worldwide have been instrumented with strong-motion sensors for the sole purpose of cataloging structural response to damaging and potentially damaging earthquakes [1, 2]. Engineers and seismologists use these data to further our understanding of actual building dynamic behavior, ultimately leading to advancements in research (e.g. damage detection) and building codes (e.g., improved empirical relations [3]). Over time, the cost-bearing public (owners and residents) indirectly benefit from this work by owning and residing in safer structures. However, there is also opportunity for the public to benefit directly from earthquake monitoring technology. Recent and not so-recent advances in client-based information-driven services has led to a new application of strong-motion instrumentation; business continuity.

Although the concept of using strong-motion data to the benefit of building owners has been considered by [4], in the opinion of the authors, it has only recently been implemented as a holistic, commercially viable solution for business continuity. We attribute this to a combination of strategic academic and industrial partnerships, advantageous commercial opportunities, and a growing body of knowledge and experience on the topic. Therefore, this paper presents a genuine business continuity solution based on strong-motion monitoring, performance-based earthquake engineering (PBEE) principles, and standard-of-care for post-disaster safety assessments.

1.1 Background

Occupants in essential facilities such as hospitals, emergency operations centers, strategic military installations, critical financial institutions, tall buildings, and nuclear power plants, cannot easily evacuate immediately after an earthquake or 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 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 [5, 6]. Critical financial institutions cannot afford unnecessary evacuations following an earthquake as these eventually turn into losses due to downtime and business disruption. Evacuation of tall and ultra-tall buildings has to be phased and causes extreme distress on stair-going evacuees.

In earthquake-prone areas the inspections performed by municipalities and mutual aid volunteer inspectors can takes several days to weeks to occur after the earthquake [6]. Funded by the Federal Emergency Management Association (FEMA) and initially deployed by the American Technology Council (ATC) in 1989, *ATC-20: Post-Earthquake Safety Evaluation of Buildings Procedures*, is the standard of care in the United States and around the world for determining if buildings are safe to occupy after an earthquake [7]. The outcome of an ATC-20 evaluation is to placard a building as Red-Unsafe, Yellow-Restricted, or Green-Inspection. For smaller, simpler facilities, rapid post-disaster safety assessments are sufficient; however, for essential facilities (e.g. hospitals, emergency operation centers, fire stations, etc.) and larger, more complex buildings, detailed post-disaster safety assessments are required to determine building safety. This is often at the owner's expense [6]. In order to avoid these unnecessary evacuations and minimize expensive downtime, a proactive system solution to rapidly perform detailed and accurate post-earthquake safety assessments of these facilities is needed.

San Francisco and several other forward-thinking jurisdictions have established Building Occupancy Resumption Programs (BORP) that permit a contracted engineer to be pre-deputized to perform ATC-20-based post-earthquake safety assessment in lieu of official inspectors [6, 7]. This has led to engineering companies offering "on-call" post-event assessment services. Partnering with structural engineering consultants (Reid Middleton), the US Navy developed a similar innovative Rapid Evaluation and Assessment Program (REAP™) for several their west coast hospitals and medical facilities [8].

REAP is a first-response tool designed to quickly determine if a facility is safe to occupy and operate following a major earthquake. REAP helps facility staff make reasonable and timely recommendations to the facility manager regarding the safety and operability of the facility. It helps accelerate the post-earthquake evaluation process and reduces the uncertainty related to the safety of the building for the decision-makers responsible for determining if the building is safe to occupy. The REAP is developed for use by engineering staff, but may be used by other first-responder personnel as needed to provide a recommendation for the facility.

A key aspect in the REAP process is the onsite safety inspection. Traditional visual-based 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 fireproofing. 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 [9]. Prolonging expensive downtime, limited resources such as qualified inspectors may not be immediately available after a damaging event, especially for dense urban areas. To streamline the response process and minimize conservatism, the combination of advanced structural health monitoring systems integrated with REAP tailored to the characteristics and vulnerabilities of a specific structure, empower onsite response teams to more rapidly, more accurately, and more confidently make critical decisions on evacuation and re-entry. Over the past decade, this solution has been implemented in several structures, Fig. 1, most notably along the US West Coast and in UAE [10, 11, 12, & 13].

Fig. 1 – Worldwide sample of Structures Implemented with REAP and/or OASIS.

1.2 UAE Experience

Several buildings in Abu Dhabi and Dubai have been equipped with permanent structural health monitoring systems as part of several recent and ongoing municipal and private projects. The primary goal of these systems is to empower the owners and managers of these facilities with information useful for making informed building occupancy decisions and avoid unnecessary evacuations similar to those that have occurred over the past few years, Fig. 2.

Fig. 2 – Earthquakes (left) resulting in evacuations (middle and right) in Dubai and Abu Dhabi during 2013-14.
Data Source: Dr. Kamal Mohamed Atiya, Survey Department, Dubai Municipality

An overview of the business continuity solution consisting, of structural health monitoring system (SHM) and its integration within the PBEE-based structural safety limits and the Rapid Evaluation and Assessment Program (REAP^{TM}) is provided in the following sections. Case studies are then presented for the recent work in UAE.

2. Structural Health Monitoring System Overview

A customized structural health monitoring system continuously monitors important response parameters that indicate structural performance, advises on the continued operation of the building, and rapidly disseminates this critical information. The SHM system described here is the OASIS (On-line Alerting of Structural Integrity and Safety) system from Kinemetrics, Inc., Fig. 3. The OASIS 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 monitoring system consists of three major hardware subsystems: sensors (accelerometers), data acquisition unit (DAQ), and the PC display and alarm cabinet.

2.1 Sensors

Accelerometers are the sensor of choice due to their robustness and ease of installation. For buildings, interstory drift is the critical response quantity of interest, but since no sensor currently exists that can reliably measure relative story displacements [14], double numerical integration is performed on the real-time acceleration data. This difficult method requires several signal processes such as linear band-pass filtering and is one of the primary functions of the OASIS software described in Section 3.3.

In addition to accelerometers, almost any type of sensor (e.g. wind sensors, strain and displacement transducers, crack meters, etc.) can be integrated to address unique structural or specific monitoring objectives.

2.2 Data Acquisition Systems

Data recorders or digitizers provide the necessary tools for continuous real-time and event-driven data acquisition, such as precise timing for synchronization, power supply and management, signal processing, analog-to-digital conversion, and file archiving. In general, there are two types of recorder deployment strategies: centralized and distributed.

Central data recorders, compared to wireless distributed recorders, remain the best commercially viable solution for demanding applications requiring robust permanent systems. Although running long analog sensor cables can be expensive, wireless technology, while promising, is not yet reliable enough to be implemented for real-world, commercial applications. Wireless-power for example is still in technological infancy and probably will be for some time. Thus, replacing analog cabling with wireless technology (or distributed recorders) requires local power supply at each sensor (or recorder) location, which consequently increases upfront costs in both hardware and implementation, as well as in maintenance demand. This is particularly true considering that sensors are typically located in difficult areas to access, such as above ceilings and in utility chases. Another challenge with wireless technology stems from the limited data buffering capacity at the sensor node preventing packet re-transmission leading to permanent data gaps, which negatively impact overall results and real-time processes.

With the onset of IEEE 1588-2008 standard for Precision Time Protocol (PTP) [15], a previously less-than-successful deployment layout has re-emerged as a potentially preferable alternative: wired distributed recorders. Previous attempts to use serial-based or NTP for digitizer clock synchronization over IP networks were not accurate enough for seismic applications (observed errors on the order of few milliseconds) [16]. PTP enabled digitizers on a PTP-compliant network will be able to synchronize their clocks to within a microsecond, comparable to GPS. As PTP-compliant network devices become ubiquitous, this deployment layout will certainly become very attractive and economically competitive approach. The issue with distributed power sources can be resolved with Power over Ethernet injectors. The one caveat is the 100m length limitation of standard Ethernet protocol. The use of fiber optic media resolves the distance restraint for data, but not for power. However, for buildings, a nodal distance constraint of 100m is rarely an issue.

2.3 Alarm and Display Cabinet

The alarm and display cabinet consists of an industrial server/computer running the necessary software, alarm panel, required network devices, and independent backup power. SHM software running on the server is responsible for controlling the alarm panel, performing real-time processes (e.g., double numerical integration), providing interactive and remote (web) display for user control, building event reports and sending message notifications (e.g., via email, SMS).

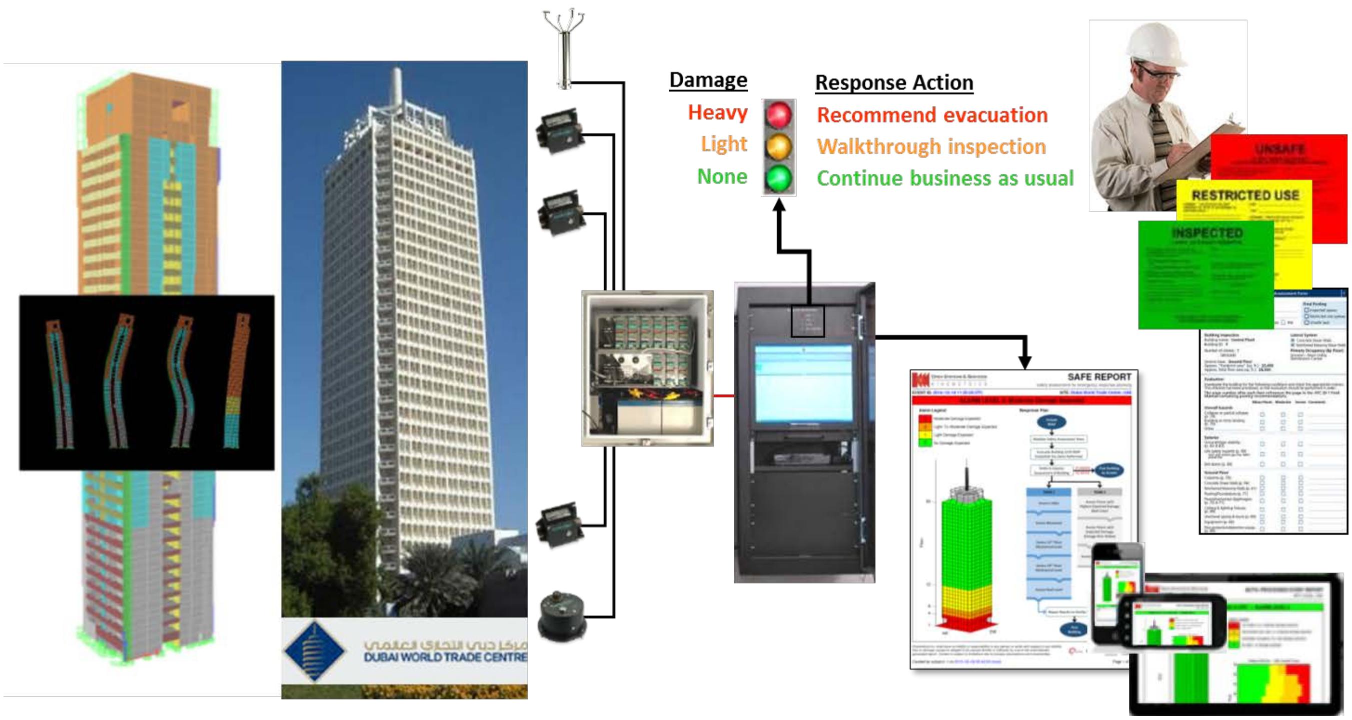

Fig. 3 – Conceptualization of OASIS and REAP integration

3. PBEE-Based Evaluation

The principal function of the SHM system described here is to compare measured building responses during a dynamic event to predetermined thresholds corresponding to various performance levels, Fig. 3. That is, the objective of the system is to answer the questions: “How much did the building move?” and “How much movement is too much?”

In order to quantify movement, the parameter that best indicates building performance and potential for global structural damage, instabilities, and safety concerns is inter-story drift. For example, knowing that the top floor moved one meter is interesting, but does not indicate how much stress is in the building and how safe the building may be. Therefore, the purpose of the building evaluation is to calculate the levels of relative movement between measured floors at which safety is a concern. Therefore, for example, knowing that the building is leaning ½% and that it is expected to elastically lean 1% without concern provides building managers with the knowledge of the building safety and empowers them to confidently make a more informed decision not to evacuate.

In reality, there is not a single value for the amount of movement the building can take, but rather a spectrum of performance levels. Therefore, in order to define these performance levels, performance-based earthquake engineering (PBEE) methodologies following the *American Society of Civil Engineers Seismic Evaluation and Retrofit of Existing Buildings* (ASCE 41-13) [17] standard are employed to establish three standard levels of performance: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Where the building's response falls on this spectrum of performance ultimately guides the post-event response action for a particular event. However, the objective of this solution is not to simply identify the building's performance based on PBEE standards, but rather to provide guidance on an action plan for evaluating the post-earthquake safety of the building. Therefore, the PBEE performance limits of the building are integrated with the *ATC-20: Post-Earthquake Safety Assessment* protocols to define building performance limits that best represent the post-earthquake safety of the building. As depicted in Fig. 4, several factors go into this process for determining the SHM performance limits, including PBEE standards, analytical modeling, past earthquake performance, component evaluations, and empirical research.

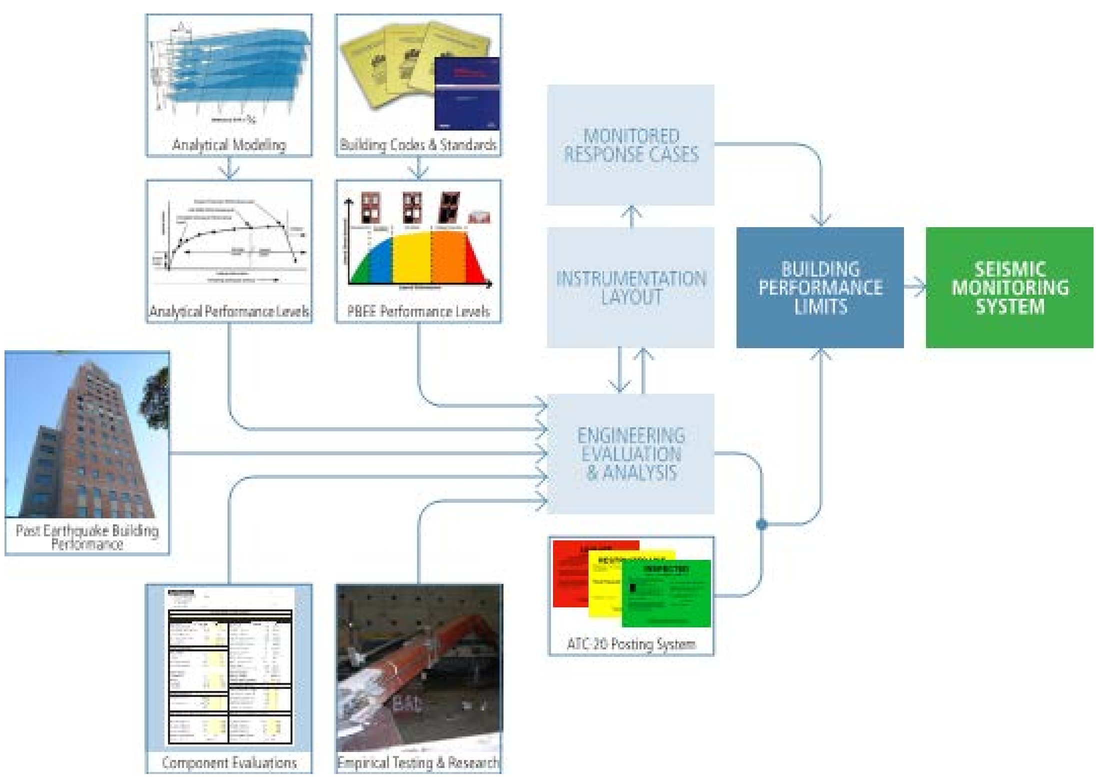

Fig. 4 – Conceptualization of OASIS and REAP integration

Additionally, it is important to note that the collapse of and damage to non-structural systems (e.g., interior partitions, HVAC, plumbing, windows, furniture, equipment, etc.) often pose the greatest risk to occupants and cause buildings to be inoperable. However, it is impractical to directly measure how the multitude of non-structural systems dynamically move and perform in an earthquake. Therefore, an essential component of the rapid post-earthquake safety evaluation is assessment is visual assessment of the performance of the non-structural systems.

3.1 Rapid Evaluation and Assessment Program

The Rapid Evaluation and Assessment Program (REAP) is an innovative first-response tool developed by Reid Middleton, Inc. structural engineers that utilizes building-specific structural analysis techniques, designed to provide building owners and facility managers with the ability to rapidly evaluate the post-earthquake condition of their facilities to improve building occupant safety and increase business continuity. REAP includes inspection and structural/non-structural evaluation information and checklist tools tailored to the characteristics and vulnerabilities each building. REAP is enhanced by the design and deployment of a real-time Seismic Monitoring System (SMS) that records and evaluates a building's forces, velocities, and displacement based on special algorithms developed through a performance-based structural analysis of each building. Corresponding performance-based earthquake engineering services are required to identify inter-story drifts corresponding to the building's seismic performance levels. It is essentially a data processing system and emergency response plan that utilizes technology to collect raw data (e.g. floor acceleration data), translate it into useful information (e.g. maximum inter-story drifts), and provide actionable knowledge (e.g. comparison with PBEE performance thresholds) for the building owners, Fig. 5.

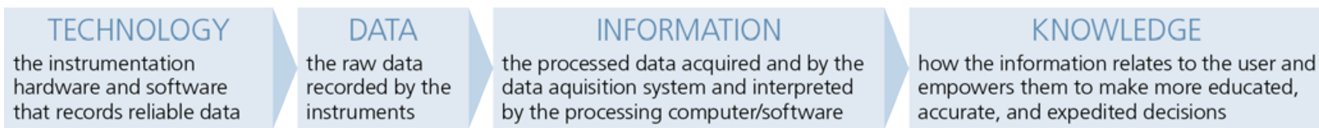

Fig. 5 – Conceptualization of OASIS and REAP integration

4. Case Studies

Case studies from several buildings are presented here.

4.1 Abu Dhabi SHM Network

To assist with sustainable development of the Emirate of Abu Dhabi, and cultivate a more disaster-resilient living environment for its citizens, the Abu Dhabi Municipality initiated the project "Assessment of Seismic Hazard and Risk in Emirate of Abu Dhabi" [11, 12]. The primary objective was to develop a state-of-the-art system to assess, monitor, mitigate, and update the seismic hazard and risk body of knowledge that exists in the Emirate. As part of this large innovative project, tasks included PBEE analyses of 18 select buildings and the implementation of permanent structural health monitoring network of seven unique and tall buildings distributed throughout the Emirate, Fig. 1.

Several years after the completion of the Abu Dhabi SHM Network, in April 2013, two large earthquakes struck the region of southern Iran Fig. 2. ShakeMaps created by USGS [18] and the new Abu Dhabi network for the M7.7 2013-04-16 Sistan-Baluschestan earthquake are shown in Fig 6. Although a significant distance away (approximately 800 kilometers) and producing relatively low amplitudes of structural response, both events resulted in mass evacuations across many Gulf countries including the United Arab Emirates. One obvious explanation for the understandable widespread reaction is that the region is simply not accustomed to seismic activity due to the infrequency of ground motions perceptible to humans. However, through careful examination of the data from the instrumented tall buildings, there are additional potential reasons why evacuations in the United Arab Emirates were so prolific in these distant events [12, 19]. Results from these examinations are not displayed here because they have already been well-published in the referenced articles. The conclusion reported was that shaking above the level of human perception lasted for over 10 minutes in some tall buildings [12]. Clearly, such long lasting shaking would bring about discomfort, even with inhabitants with prior earthquake experiences in active seismic regions.

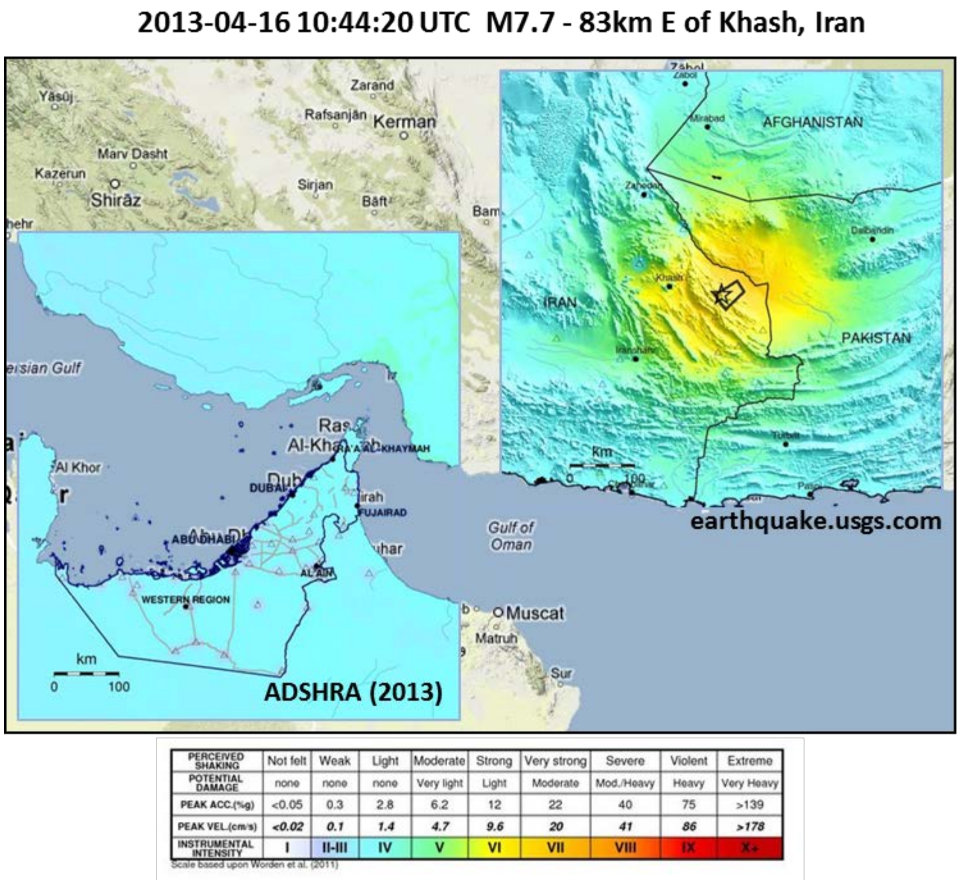

Fig. 6 – USGS and

4.2 Dubai SHM Network

The Survey Department of the Dubai Municipality, as part of its ongoing activities to provide real-time monitoring of seismic activity in the region and create public awareness, chose two important and iconic buildings to implement SHM systems including response planning. The primary objectives are to prevent unwarranted distress among Dubai citizens, reduce business interruption caused by unnecessary evacuations, and minimize periods of downtime waiting for official decision to reoccupy [13]. These buildings are the Shaikh Rashid Tower at the Dubai World Trade Centre (DWTC), the oldest tower in Dubai, and the Burj Khalifa, the tallest building in the world shown in Fig. 1.

At DWTC, for example, a customized response plan (REAP) based on the unique structural characteristics and ATC-20 post-earthquake evaluation procedures was developed as shown on Fig 7-left below. The monitoring system provide red-yellow-green alarms for on-site security and emergency response team to take appropriate actions after an earthquake such as initiate REAP. Alerts with automatically-generated reports displaying the building response status and corresponding response actions (Fig 7-right) and will be sent to the designated officials to support their emergency response decisions. Onsite response team members were trained on the plan and annual testing (similar to fire alarm testing) is expected to be implemented along with re-training, as necessary.

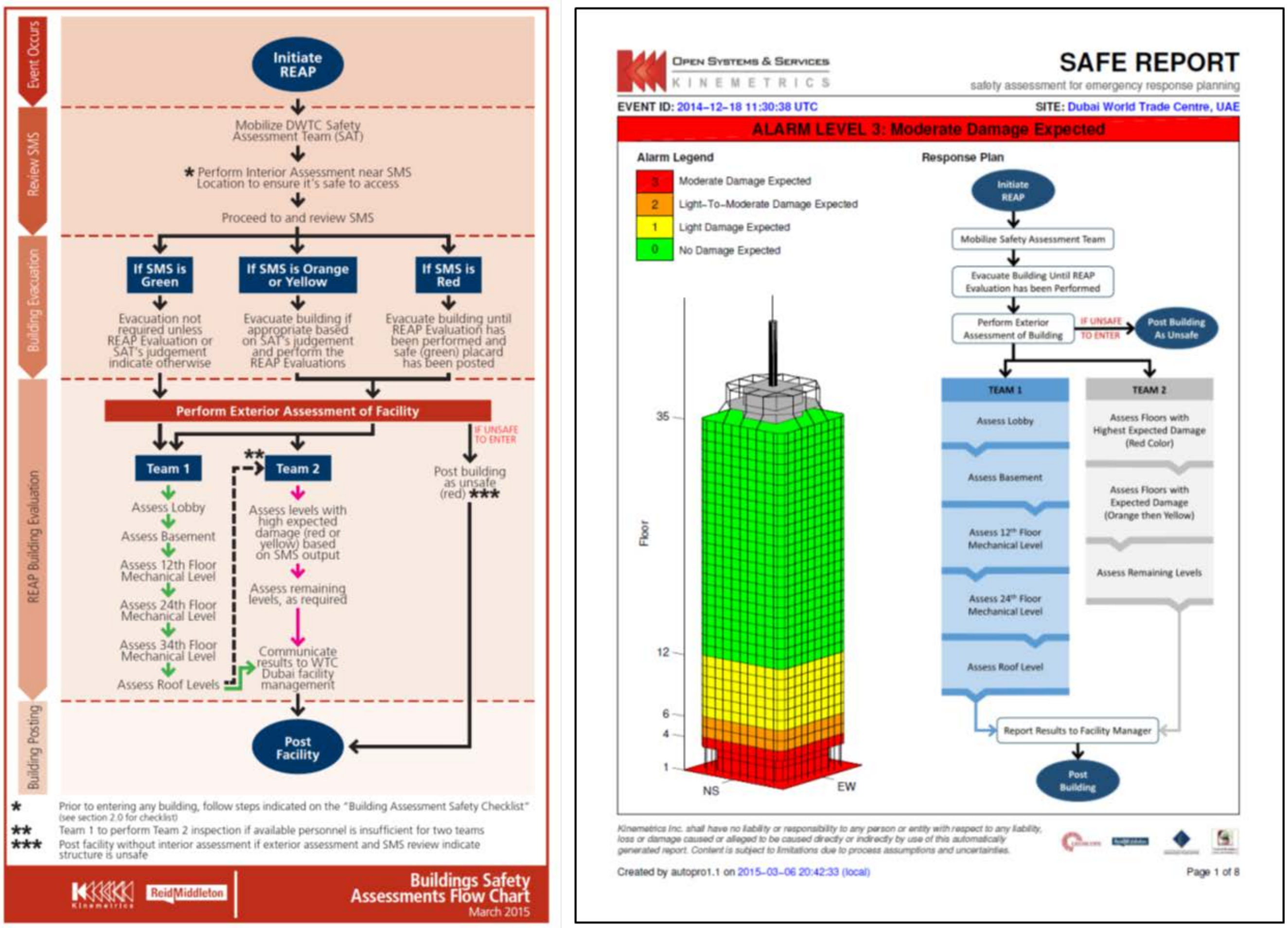

Fig. 7 – Full REAP flow chart for DWTC (left) and SAFE Report for fictional scenario level 3 event

The system alerts and reports will help the safety team decide how and when to evacuate the building and the subsequent decision on when to reoccupy. This will help avoid unnecessary evacuation such as those that took place during the April 2013 events. Office towers and other high-rises in Dubai were evacuated and people spent hours in the open due to the impact of earthquakes that shook Iran on April 9 and 16, respectively. A repeat of these evacuations occurred again on July 30, 2014 after a 5.3 magnitude earthquake hit near southern Iran's Kish Island, less than 200 km northeast of Dubai.

News media reports described in detail the distress and confusion created by these events and the prolonged hours of downtime that hotels, office buildings, and others experienced. This lead to financial losses, which have not yet been quantified, but are estimated to be significant, considering that the DWTC fuels 2.2% of the emirates GDP (2012) [20].

5. Conclusions

Structural health monitoring systems, such as Kinemetrics OASIS, provide timely information that can be extremely useful if the processing/reporting is well-integrated within a post-earthquake safety inspection plan such Reid Middleton's REAP. Experiences gained through projects such as those presented as case studies here offer invaluable insight into what is required to implement a comprehensive response plan to improve occupant and business continuity.

Furthermore, widespread implementation of fully comprehensive business continuity solutions to earthquakes, will inevitably lead to improved economic resilience of smart, building-rich communities such as UAE cities.

In general, the benefits of implementing a solution like this can be summarized as follows:

1. Occupant confidence and safety is improved, avoiding panicked crowds.

2. Building Owners save money by reducing costly downtime and business interruption caused by unwarranted evacuations.

3. Facility Managers are better-equipped to make informed decisions on evacuation and reoccupation.

4. Policy Makers improve safety mandates for the public and showcase city's resilience and growth.

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7. Copyrights

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