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EARTHQUAKE BUSINESS CONTINUITY USING SHM, PBEE RAPID EVALUATION, RESPONSE, AND NOVEL COMMUNICATION

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ABSTRACT

Buildings worldwide have been instrumented with seismic and structural health monitoring systems for the purpose of understanding structural response to damaging and potentially damaging earthquakes. These data are used to further our understanding of actual building dynamic behavior, ultimately leading to advancements in research and building codes. In the long term, the cost-bearing stakeholders indirectly benefit from this work by owning and residing in safer structures. However, there is opportunity for a direct benefit from this type of monitoring. Recent advances in client-based information-driven services has led to a new application; earthquake business continuity. This paper presents an earthquake business continuity solution based on seismic and structural health monitoring, performance-based earthquake engineering (PBEE) principles, standard-of-care for post-earthquake safety assessments, and a novel technology-based communication platform.

Occupants in essential facilities such as hospitals, military installations, and government institutions as well as other critical structures such as financial institutions and ultra-tall buildings, cannot easily evacuate immediately after an earthquake or wait for detailed safety assessment to reoccupy and resume operations. These decisions are difficult, especially under state of distress, and can have dire consequences if made incorrectly or too slowly (e.g. panic related injuries, losses 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.

Keywords: Earthquake Business Continuity; SHM; ATC-20; PBEE; Emergency Response Planning

1. INTRODUCTION

Most instrumented buildings with seismic and structural health monitoring systems focused the purpose of this on recording structural responses to damaging and potentially damaging earthquakes, like is the case in California with the State of California Strong Motion Instrumentation Program (2017) and the USGS National Strong Motion Project (2017). This recorded data is used to further understanding of actual building dynamic behavior, ultimately leading to advancements in research (e.g. damage detection) and building codes e.g., improved empirical relations, Goel RK and Chopra AK (1997.) Over time, the cost-bearing public (owners and residents) indirectly benefit from this work by owning and residing in safer structures. However, there is opportunity for the public to benefit directly from earthquake monitoring technology. Advances in client-based information-driven services has led to a new application of seismic monitoring; earthquake business continuity.

Although the concept of using strong-motion data to the benefit of building owners has been considered in the past, Celebi M et al. (2004), it has only recently been implemented as a holistic, commercially viable solution for business continuity, as a result of strategic academic and industrial partnerships, commercial opportunities, and a growing knowledge and experience on the topic.

In the United Arab Emirates (UAE), for example, occupants in very tall buildings have endured long-duration swaying due to large distant earthquakes originating in southern Iran. This prompted

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municipal and private entities to equip several critical buildings with Structural Health Monitoring (SHM) systems to alert on exceedance of structural safety performance thresholds, and implementation of rapid earthquake response planning, and a novel communication platform 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 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 this complete solution along with some case studies.

2. BACKGROUND

Occupants in essential facilities such as hospitals, public services organizations, 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. For example, 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, BORP (2001), ATC-20 (1989). Similarly, public services organizations cannot afford unnecessary evacuations following an earthquake as these eventually turn into losses due to downtime and business disruption and even more importantly, the interruption of the very services the public count on in emergencies. Also, 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 take several days to weeks to occur after the earthquake, BORP (2001). 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, ATC-20 (1989). 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 and larger, more complex buildings, detailed post-earthquake safety assessments are required to determine building safety. This is often at the owner's expense, BORP (2001). 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 the Building Occupancy Resumption Program (BORP) that allow contracted engineers to be pre-deputized to perform ATC-20-based post-earthquake safety assessment in lieu of official inspectors, BORP (2001), ATC-20 (1989).
However, 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. 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 system integrated with response planning, 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, Figure 1, most notably along the United States West Coast and in the United Arab Emirates, Skolnik DA et al. (2012), Milutinovic ZV et al. (2013), Skolnik DA et al. (2014), & "Dubai Municipality Survey Department, Bulletin of Dubai Seismic Network" (2014).

Figure 1. Sample of structures implemented with complete or parts of earthquake business continuity solution

In the case of Abu Dhabi and Dubai, several buildings 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, Figure 2.
An overview of this earthquake business continuity consisting of structural health monitoring system (SHM) and its integration within the PBEE-based structural safety limits and a response planning with a technology-based novel communication platform is provided in the following sections. Case studies are then presented for the recent work in the United Arab Emirates.

3. OASISPLUS SOLUTION OVERVIEW

The Earthquake Business Continuity Solution described here is OasisPlus from Kinemetrics, Inc. and provides the tools and information needed to control impact, minimize downtime, and reinforce crisis management with effective communications before, during, and after an earthquake, see Figure 3. The solution is based on four key areas: Monitoring, Alarm System, Rapid Post-Event assessment, and a Novel Communication Platform.

3.1 Monitoring

The structural health monitoring technology refers to high-end instrumentation that continuously monitors important building response parameters such as interstory-drift that indicate structural performance. It provides data that answers the question: *how much did my building move?*

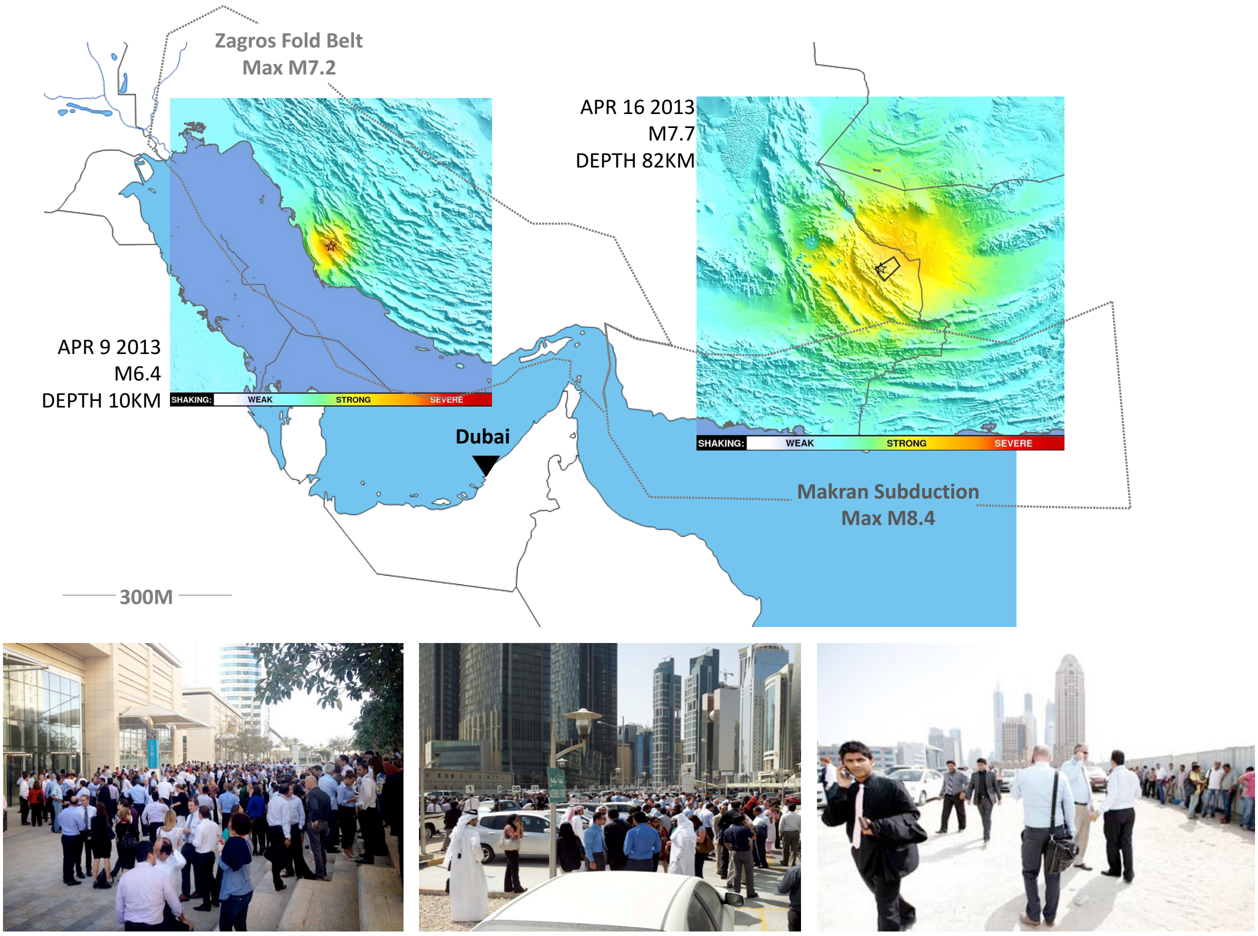

Figure 2. Gulf region showing seismic hazard sources with April 2013 USGS ShakeMaps® (top) resulting in evacuations (bottom) in Dubai and Abu Dhabi (Sources: Emirates 24|7 News, UAE National and Daiji World)

Figure 3. OasisPlus provides the tools and information needed before, during & after an earthquake

Figure 4 shows an example of the structural health monitoring system consisting of three major subsystems: sensors (accelerometers), data acquisition unit (DAQ), and the display cabinet.

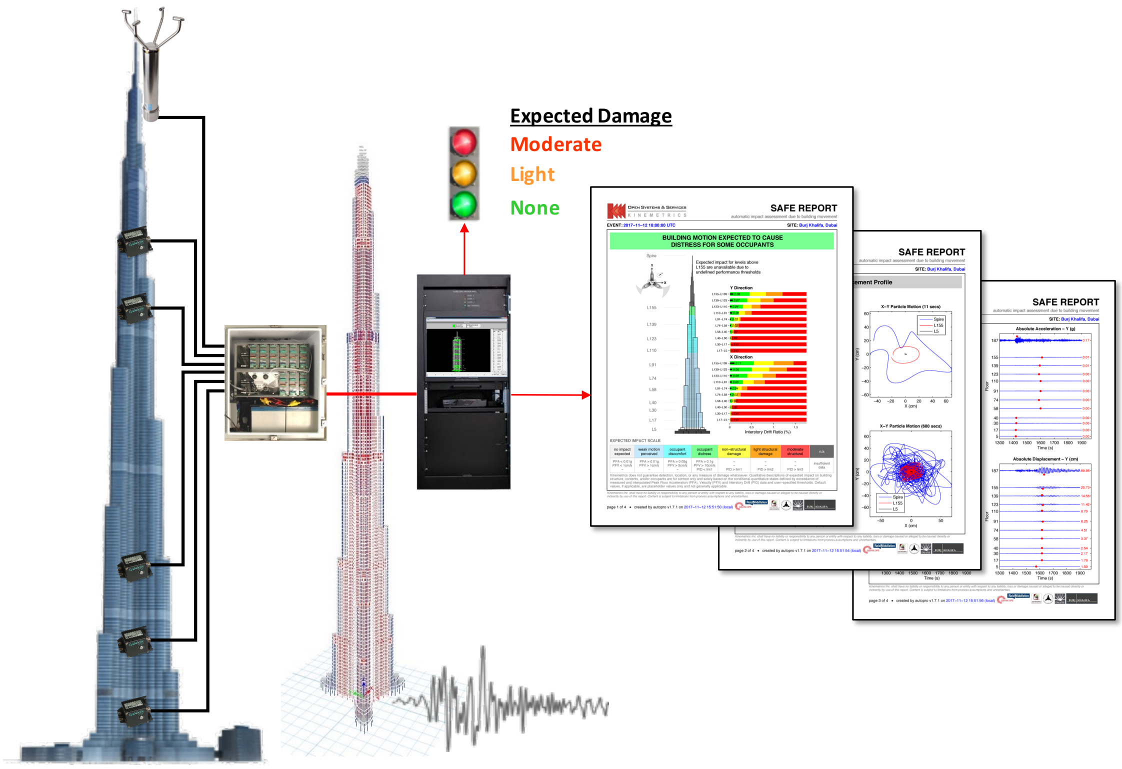

Figure 4. Structural health monitoring system

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, Skolnik DA and Wallace JW (2010), double numerical integration is performed on the real-time acceleration data.
This difficult method requires several signal processes such as linear band-pass filtering. 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.
Data Acquisition System: 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.
Display Cabinet: The 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 display for user control, building event reports and sending message notifications (e.g., via email, SMS).

3.2 Alarm System

An alarm system provides intuitive alerting on exceedance of multi-level demand parameters that come from a detailed seismic evaluation of the building structural and non-structural systems (using ASCE-41, for example). Along with the monitoring element, the alarm system effectively converts data into actionable information. It answers the question: *how much is too much or could there be a safety concern?*

The principal function of this system is to compare measured building responses during a seismic event to predetermined thresholds corresponding to various performance levels, Figure 5.

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. For instance, knowing that the building is leaning 1/2 % 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 (2014), standard is employed to establish three standard levels of performance: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

Specifically, alarm levels are based on a unique combination of peak floor acceleration, velocity, and interstory drift threshold exceedances. Typically, the lower limits of acceleration and velocity are meant to provide information on human perception of shaking intensity. While the upper interstory drift limits are initially based on the standard performance limits as mentioned above. It should be noted that upper level alarms are meant to trigger specific post-event actions such as inspection points and thus are highly specific to a buildings' facility/operation team and not just the structure itself. Additionally, intermediate alarm levels can be used to inform on the potential of damage to non-structural elements.

3.3 Rapid Post-Event assessment

A rapid post-event assessment program, such as REAP®, Swanson DB et al. (2011) based on ATC-20, provides the highly-customized onsite procedures for rapid safety assessment of the building. It instills preparation and confidence in the facility operators leading to quicker and more confident decision making. It answers questions on severity such as: *do we need to evacuate?*

Where the building's response falls on this spectrum of performance ultimately guides the post-event response action for a particular event. Connecting the Emergency Response planning closely to the Alarm system. Fulfilling one of the objectives of the solution to not 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, Skolnik DA et al. (2017). As depicted also in Figure 5, 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.

3.4 Novel Communication Platform

A novel communication platform is the final component for greater situational awareness, streamlined decision making, and information dissemination. Complimentary to conventional public announcements and red/yellow/green tagging, OasisPlus introduces web control and mobile notifications to help manage evacuation/re-entry decision making and process. It facilitates two-way communication between occupants and crisis management allowing for instant check-ins, hazard reporting, post-event checklist gathering, etc. This answers the key question: *how to communicate the instructions?*

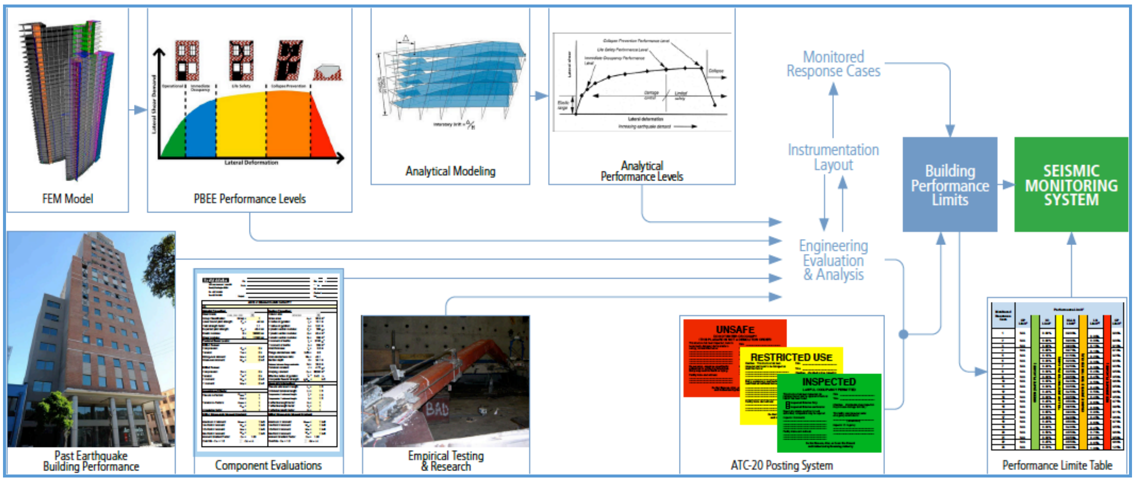

Figure 5. From alarm system to a rapid post-event assessment program, REAP®

Figure 6 shows OasisPlus mobile application screens for information dissemination before, during, and after the earthquake.

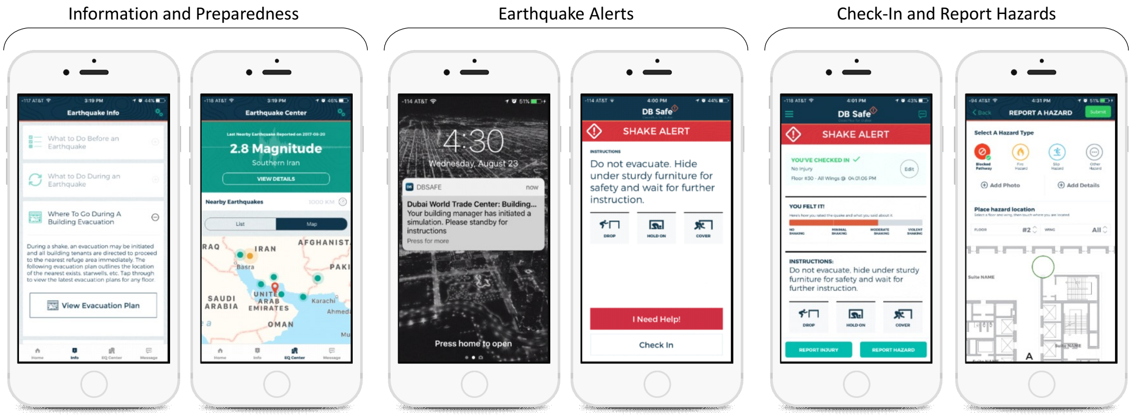

Figure 6. OasisPlus mobile application

4. CASE STUDIES

Abu Dhabi: 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 - ADSHRA", Milutinovic ZV et al. (2013), Skolnik DA et al. (2014). 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, Figure 1.
After the completion of the Abu Dhabi SHM Network, in April 2013, two large earthquakes struck the region of southern Iran Figure 2. 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, Skolnik DA et al. (2014), Safak E et al. (2014). 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, Skolnik DA et al. (2014). Clearly, such long lasting shaking would bring about discomfort, even with inhabitants with prior earthquake experiences in active seismic regions.

Dubai: 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 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, "Dubai Municipality Survey Department, Bulletin of Dubai Seismic Network" (2014). These buildings are the Shaikh Rashid Tower at the Dubai World Trade Centre (DWTC), the oldest tower in Dubai, the Burj Khalifa, the tallest building in the world, the Dubai Municipality, and the Dubai Police Department, some of these shown in Figure 1.

At DWTC, for example, a customized response plan based on the unique structural characteristics and ATC-20 post-earthquake evaluation procedures was developed as shown on Figure 7(left). 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 response plan. Alerts with automatically-generated reports displaying the building response status and corresponding response actions Figure 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.

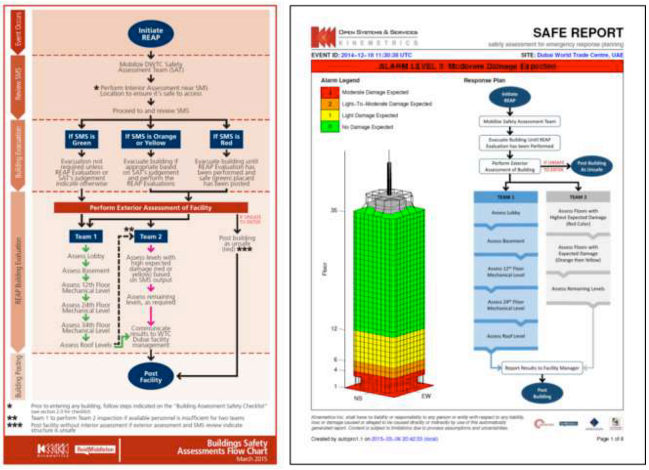

Figure 7. Full Response Plan flow chart for DWTC (left) and SAFE Report for scenario level 3 event (right)

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), The Dubai World Trade Centre: Business

under one roof (2017).
The Dubai Municipality full implementation of OasisPlus solution (branded DB-Safe project), Figure 8, is transforming the city from buildings and infrastructure into a *network of assets* whose health can be monitored during localized and regional events such as seismic activity. Turning Dubai into a more resilient city.

Figure 8. Selected buildings instrumented under the Dubai Municipality DB-Safe project.

5. CONCLUSIONS

Business continuity comes from better-informed decision making and effective information dissemination. OasisPlus is the solution to avoiding costly and potentially dangerous over-reaction by enabling better-prepared occupants and better-informed decision makers. It consists of four main components; ***Monitoring Technology*** for real-time measuring of building movement, an ***Alarm System*** for intuitive alerting on exceedance of performance-based movement thresholds, a ***Safety Assessment Plan*** for rapid post-earthquake onsite safety inspections, and a ***Communication Platform*** for greater situational awareness, streamlined decision making, and information dissemination.

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