

# Earthquake Business Continuity for United Arab Emirates Buildings Using Structural Health Monitoring and Performance-Based Earthquake Engineering Rapid Evaluation

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**Abstract:** Buildings worldwide have been instrumented with seismic monitoring systems for the purpose of cataloging structural response to damaging and potentially damaging earthquakes. Engineers use these data to further our understanding of actual building dynamic behavior, ultimately leading to advancements in research and building codes. 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. Recent advances in client-based information-driven services has led to a new application; earthquake business continuity. This paper presents earthquake business continuity solutions based on seismic monitoring, performance-based earthquake engineering (PBEE) principles, and standard-of-care for post-earthquake safety assessments.

*Occupants in essential facilities such as hospitals, military installations, 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, Structural Health Monitoring, Earthquake Response Planning, ATC-20, PBEE

## 1. INTRODUCTION

Most instrumented buildings with seismic monitoring systems centered the purpose of this on recording structural responses to damaging and potentially damaging earthquakes [1, 2]. 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 [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 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 [4], 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.

In the United Arab Emirates (UAE), occupants in very tall buildings have endured long-duration swaying due to large distant earthquakes originating in southern Iran. This prompted 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, 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 the rapid post-event assessment solution along with several 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 [5, 6]. 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 [5]. 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 [6]. 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 [5]. 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 [5, 6].

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 US West Coast and in the United Arab Emirates [7, 8, 9, & 10].



Fig. 1: Sample of Structures Implemented with Earthquake Business Continuity Solution and/or Response Planning

## 3. UNITED ARAB EMIRATES 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, Figure 2.

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 response planning is provided in the following sections. Case studies are then presented for the recent work in the UAE.



Fig. 2: Earthquake (left) resulting in evacuations (right) in Dubai and Abu Dhabi during 2013-14.

#### 4. SOLUTION OVERVIEW

The Earthquake Business Continuity Solution described here is OASIS Plus™ from Kinemetrics, Inc. and provides a framework that will control economic impact, protect access to services, minimize downtime, and reinforce communications. The solution is based on four key areas: Monitoring, Alarm System, Emergency Response, and Communications. Figure 3.



Fig. 3: OASIS Plus™ Solution Overview.

The Monitoring is a customized Structural Health Monitoring system that continuously monitors important response parameters that indicate structural performance, answering the question: *how much did the building or ground move?*

The Alarm System provides intuitive alerting on exceedance of demand/design parameters and turns data into actionable information. In other words, answers the question: *how much is too much?*

The Emergency Response implements action procedures leading to quicker and more confident decision making. Answering the questions: *is there a safety concern? what should be done?*

And the Communications area, manages the spread of information which is imperative to informing the efforts needed to deliver continuity. This answers the key question: *how to communicate the instructions?*

#### 5. STRUCTURAL HEALTH MONITORING

The standard Structural Health Monitoring is a flexible system that provides for the collection and processing of real-time acceleration, velocity, displacement, and inter-story drift data. It consists of three major subsystems: sensors (accelerometers), data acquisition unit (DAQ), and the display cabinet. Figure 4.

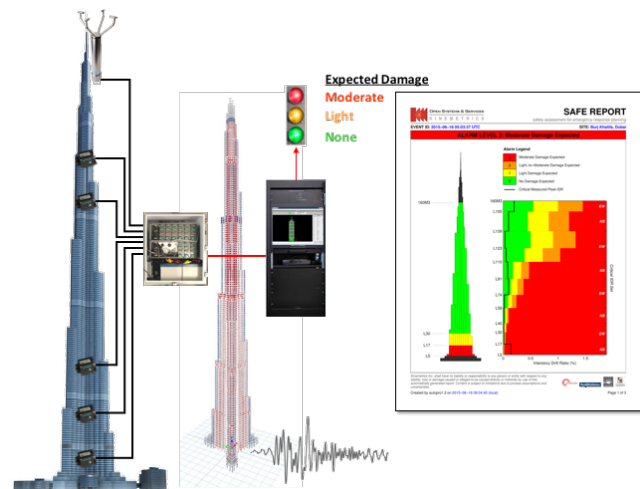


Fig. 4: SHM System

**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 [11], 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).

## 6. ALARM SYSTEM

The principal function of the Alarm system described here 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. Therefore, for example, 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) [12] standard are employed to establish three standard levels of performance: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

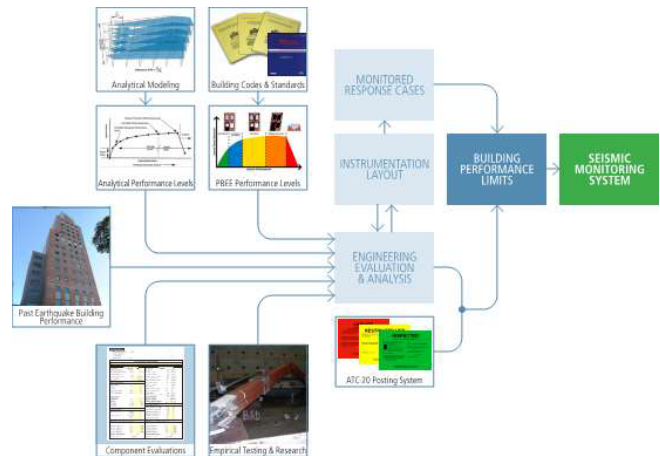


Fig. 5: From Alarm System into Response Planning

## 7. EMERGENCY RESPONSE PLANNING

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 [13]. 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.

### 8. SYSTEM COMMUNICATION PLATFORM

An effective system communication platform is the final piece that transforms a potential costly crisis into a community experience, delivering continuity. This is what effectively leads to better management of decisions when the emergency response plan is activated. Notifications can be delivered through an information display center, web browser, public announcement system, and mobile applications. This in turn facilitates a two-way communication, where notification recipients can also provide feedback to the personnel in charge of managing the emergency. Figure 6.

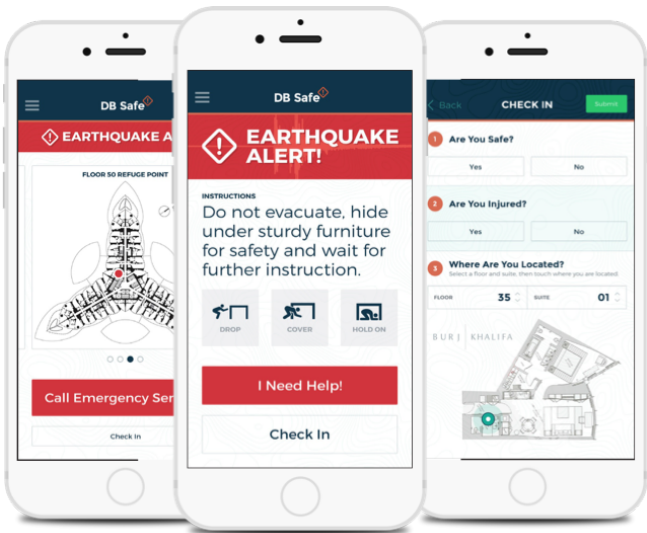


Fig. 6: System Communication Platform

### 9. CASE STUDIES

Case studies from several buildings are presented here.

**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” [8, 9]. 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.

Several years after the completion of the Abu Dhabi SHM Network, in April 2013, two large earthquakes struck the region of southern Iran Figure 2. ShakeMaps created by USGS and the new Abu Dhabi network for the M7.7 2013-04-16 Sistan-Baluchestan earthquake are shown in Figure 7. 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 [9, 14]. 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 [9]. Clearly, such long lasting shaking would bring about discomfort, even with inhabitants with prior earthquake experiences in active seismic regions.

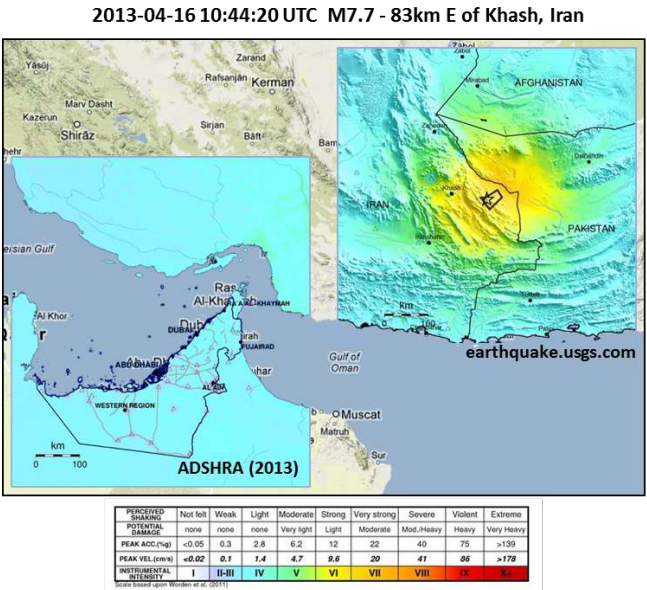


Fig. 7: Shake Maps USGS and ADSHRA

**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 [10]. 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 8(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 8(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.

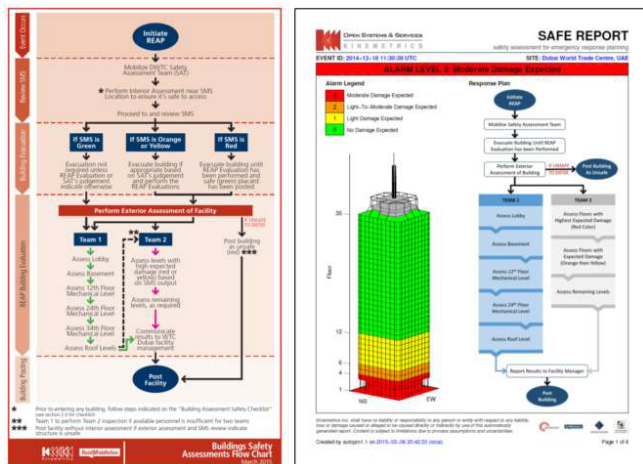


Fig. 8: Full Response Plan flow chart for DWTC (left) and SAFE Report for fictional scenario level 3 event (right)

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) [15].

The Dubai Municipality full implementation of OASIS Plus™ solution, Figure 9, 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.

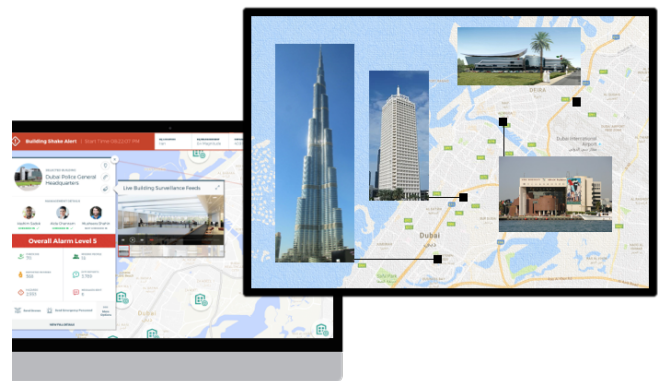


Fig. 9: Dubai OASIS Plus™ Implementation.

## 10. CONCLUSIONS

A solution, such as Kinemetrics OASIS Plus™, provide timely information that can be extremely useful if the processing/reporting is well-integrated within a post-earthquake safety inspection plan. 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 earthquake 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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