SHM + PBEE + Mobile App = Earthquake Business Continuity

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ABSTRACT

Seismic and structural health monitoring systems in buildings have improved our understanding of structural response to potentially damaging earthquakes. Earthquake data not only furthers our understanding of actual building dynamic behavior, but also leads to advancements in research and building codes. In the long term, the cost-bearing stakeholders (and society in general) indirectly benefit from this work by owning and residing in safer structures. However, recent advances in both engineering and technology have led to opportunity for a direct benefit from this type of monitoring. This paper presents a novel 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.

The solution is currently implemented in four buildings in Dubai and underway in three hospitals on the US west coast.

Keywords: SHM, ATC-20, PBEE, Emergency Response, Post-Earthquake Response.

INTRODUCTION

Beginning in the 1970's, buildings were instrumented with seismic monitoring systems aimed to record structural responses to damaging or potentially damaging earthquakes. Public programs such as California Strong Motion Instrumentation Program [1] and the USGS National Strong Motion Project [2] were charged with implementing and maintaining these systems.

The collected data were used to further our understanding of actual building dynamic behavior, ultimately leading to advancements in research and improvements in building codes [3]. Over time, the cost-bearing owners and/or occupants 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 direct 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, 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 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

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 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. In addition, 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 solution to enable rapid, 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 United States West Coast and in the United Arab Emirates [7-10].

Figure 1. Worldwide sample of Structures Implemented with Earthquake Business Continuity Solutions.

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.

Figure 2. Unnecessary evacuations in UAE from 2013 Iran event.

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.

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. The solution is based on four key areas: Monitoring, Alarm System, Rapid Post-Event assessment, and a Novel Communication Platform.

Monitoring System

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?*

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).

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 [12], 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 3.

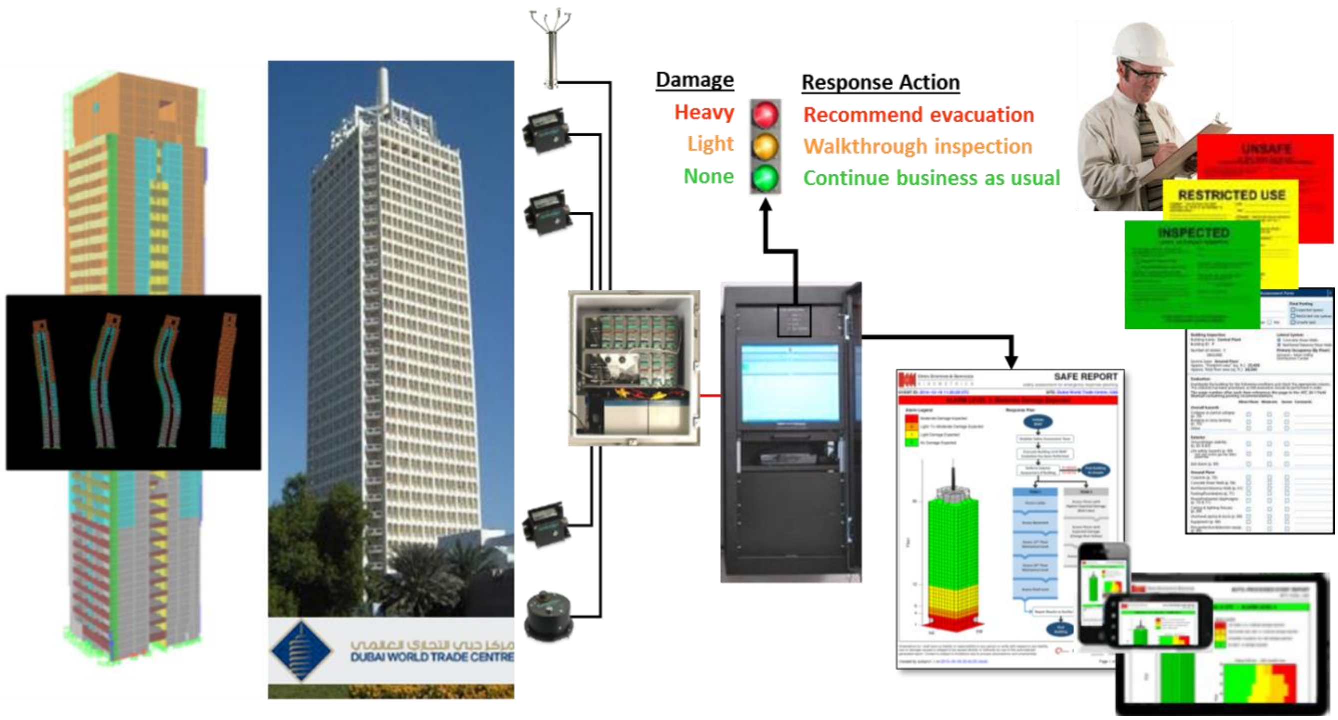

Figure 3. Conceptualization of Earthquake Business Continuity Solution.

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 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 [12], standard are employed to establish three standard levels of performance: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). As depicted also in Figure 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.

Where the building's response falls on this spectrum of performance ultimately guides the post-event response action for a particular event.

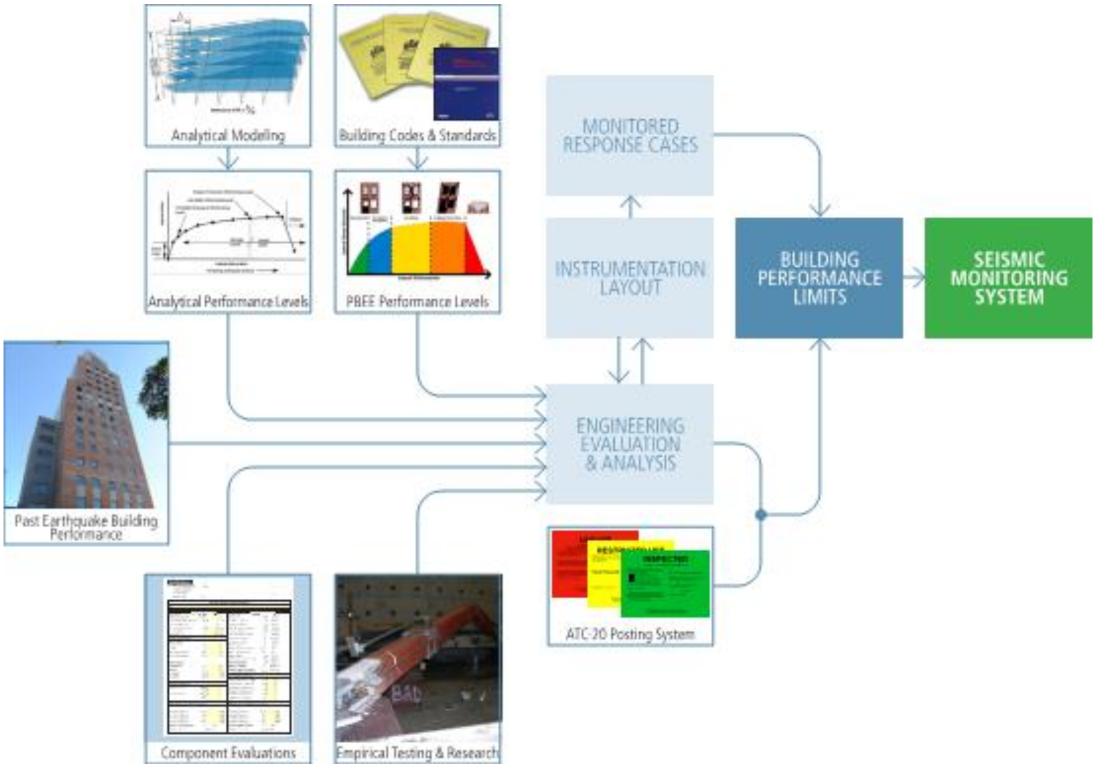

Figure 4. Conceptualization of Earthquake Response Plan.

Rapid Post-Event Response

A rapid post-event assessment program, such as REAP® [13 and 14] 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?*

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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?*

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" [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 that exists in the Emirate. As part of this large 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. 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, 15]. Results from these examinations are not displayed here because they have already been published in 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.

Dubai: The Dubai Municipality, as part of its ongoing activities to provide real-time monitoring of seismic activity in the region and create public awareness, selected four important and/or 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 5(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 5(right) are 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.

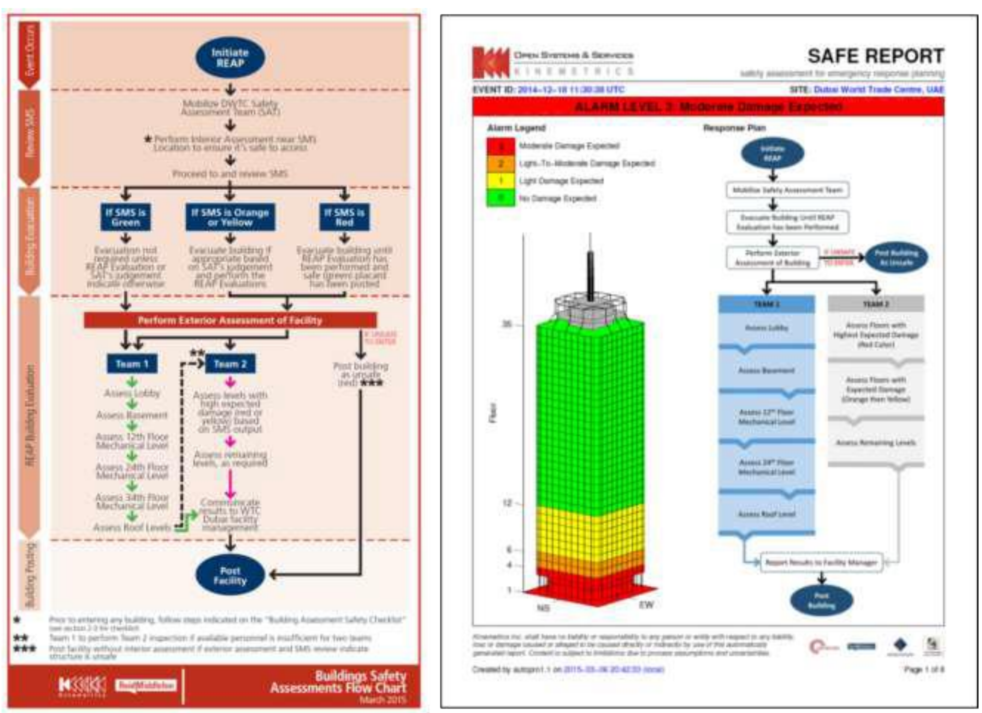

Figure 5. Response plan flow chart (left) and SAFE Report for fictional scenario level 3 event (right)

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. 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), [16]

CONCLUSIONS

Business continuity comes from better-informed decision-making and effective information dissemination. OasisPlus is designed to avoid 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.

OasisPlus has been successfully deployed in the United Arab Emirates and is currently used to support training and scenario drills. As of this paper, three hospitals on the US west coast have begun similar implementations.

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