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OASIS Structural Health Monitoring System for EPM's Intelligent Building: An Earthquake Business Continuity Solution

Ciudad-Real M.[1], Skolnik, D.A.[1], Carvajal, D.L.[2], Legarda, G.A.[2], Ojeda, A[3]

[1] *Kinemetrics, Inc. 222 Vista Ave. Pasadena, California 91107 - USA*

[2] *EPM Carrera 58 # 42-125. Medellin, Colombia*

[3] *KMA Construcciones S.A. Calle 93b No 19-21. Bogota D.C., Colombia*

Abstract: *Buildings are instrumented with seismic monitoring systems for the purpose of recording structural response to earthquakes. Engineers use this to further our understanding of 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 by owning and residing in safer structures. However, there is also opportunity for the public to benefit directly from this technology. Recent advances in client-based, information-driven services has led to a new application; business continuity.*

This paper presents an earthquake business continuity solution based on seismic monitoring, performance-based earthquake-engineering (PBEE) principles, and standard-of-care for post-earthquake assessments (ATC-20).

Occupants in essential facilities such as hospitals, public services organizations, and financial institutions, 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.). Medellin and other cities in Colombia have experienced this, even from moderate magnitude earthquakes, e.g. 6.1 Mutatá, Antioquia 13/09/2016.

The EMP's Intelligent Building was instrumented in 1999 with 24-sensor system for recording building responses, performing system identification, and tracking changes in dynamic properties. This system was upgraded in 2016 with sensors, data-acquisition, and real-time Structural Health Monitoring (SHM) system to alert on exceedance of structural safety performance thresholds, aimed to avoid unnecessary evacuation, shutdown and/or minimize downtime.

Keywords: Seismic Monitoring, Business Continuity; SHM; ATC-20, PBEE

Corresponding author's email: mcr@kmi.com

Introduction

Many buildings around the world are instrumented with seismic monitoring systems for the sole purpose of recording structural response to damaging and potentially damaging earthquakes [1, 2]. Engineers 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. 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], 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 seismic monitoring, performance-based earthquake engineering (PBEE) principles, and standard-of-care for post-disaster safety assessments.

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, in the United Arab Emirates [7, 8, 9, & 10], and recently in Medellin, Colombia.

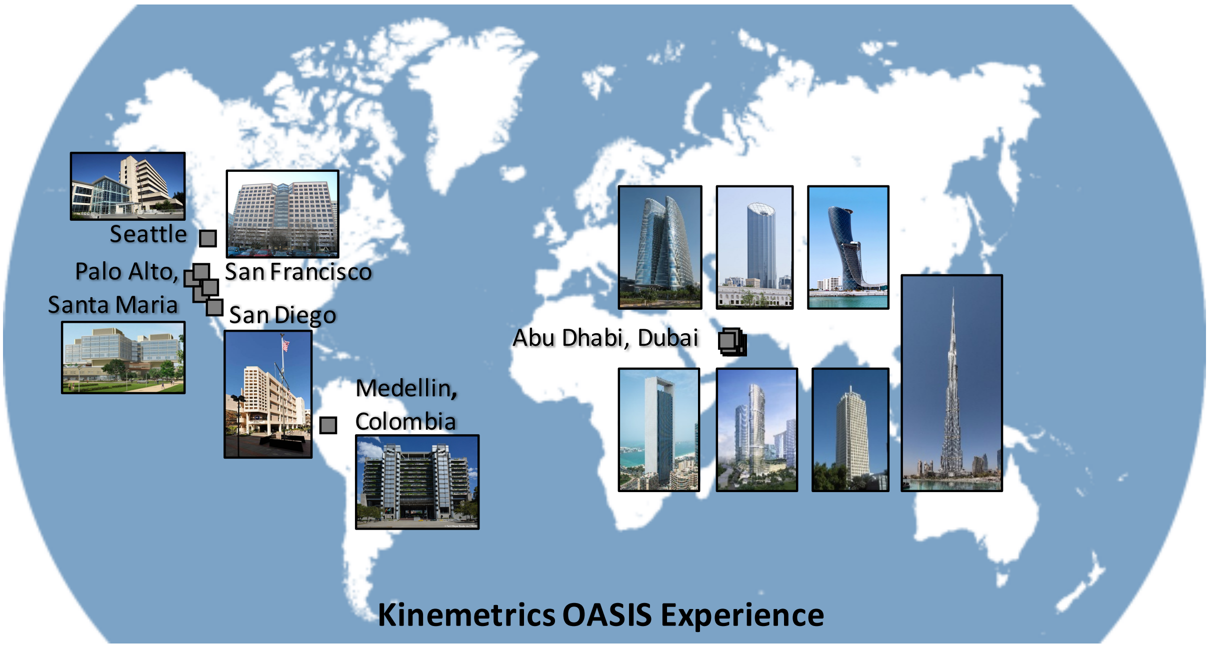

Figure 1: Worldwide sample of Structures Implemented with OASIS and/or response planning

The EPM's Intelligent Building

The EMP's Intelligent Building in Medellin, Colombia, Figure 2, was originally instrumented in 1999 with a 24-sensor seismic monitoring system for recording building responses, which has been producing data for performing system identification and tracking changes in dynamic properties. This system was upgraded in 2016 with new sensors and modern data-acquisition

system as a real-time Structural Health Monitoring (SHM) system to alert on exceedance of structural safety performance thresholds. The primary goal of this system is to empower EPM' managers with information useful for making informed building occupancy decisions and avoid unnecessary evacuations, shutdown and/or minimize downtime, similar to those that have occurred over the past few years. Even from moderate size earthquakes such as the 6.1 magnitude earthquake in Mutatá, Antioquia of 13/09/2016 or the 6.6 magnitude that occurred on 10/03/2015 in La Mesa de Los Santos, Santander, to mention just a few, Figure 3.
An overview of this solution is provided in the following sections.

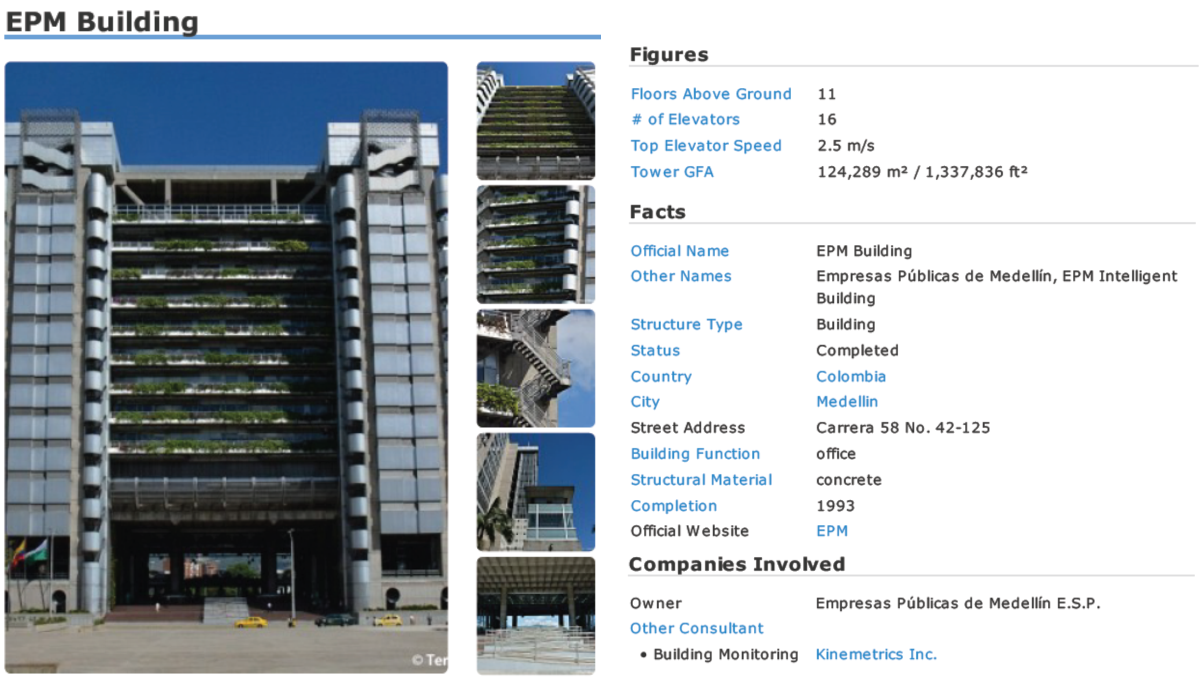

Figure 2: EMP's Intelligent Building. The Skyscraper Center - http://skyscrapercenter.com/building/epm-building/20140. Retrieve 28/04/2017

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., Figure 4. 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 system consists of three major hardware subsystems: sensors (accelerometers), data acquisition unit (DAQ), and the PC display and alarm cabinet.

Figure 3: Moderate magnitude earthquakes in Colombia have caused spread evacuations and panic. 6.1 Mutatá, Antioquia 13/09/2016. Zona Cero - http://zonacero.com.
6.6 La Mesa de Los Santos, Santander 10/03/2015 El Diario - http://www.eldiario.com.co

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 and is one of the primary functions of the OASIS software described below.
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.

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 display for user control, building event reports and sending message notifications (e.g., via email, SMS).

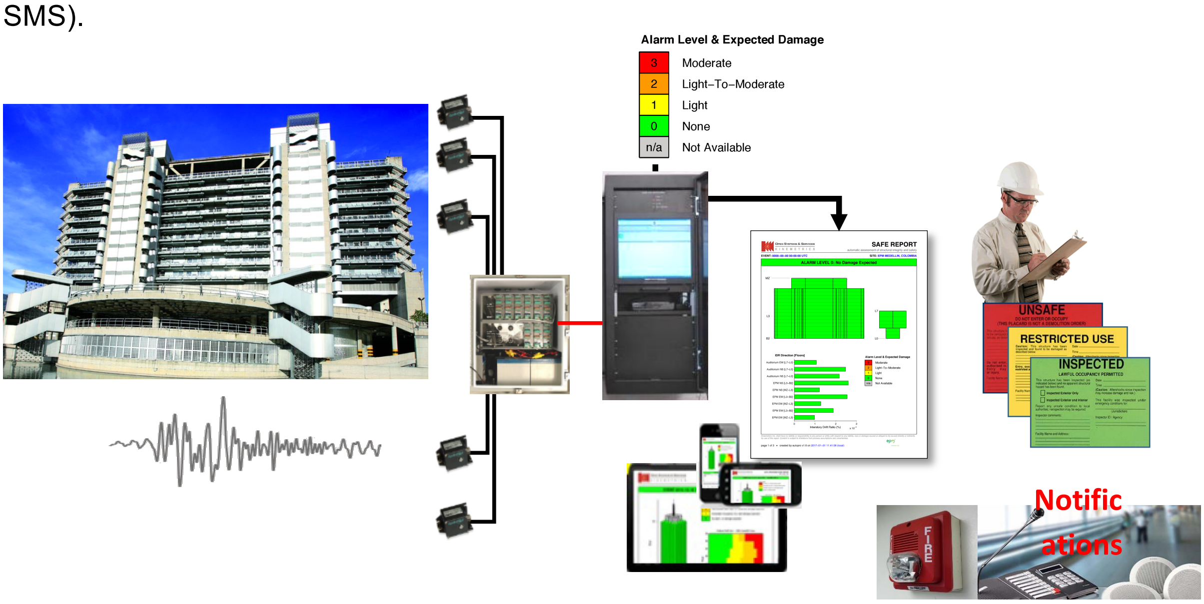

Figure 4: OASIS System Solution Overview for EMP Intelligent Building

PBEE-Based Evaluation

The principal function of the SHM system described here is to compare measured building responses during a seismic event to predetermined thresholds corresponding to various performance levels, Figure 5. 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 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).
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 [13]. As depicted 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.
In the case of the EMP's Intelligent Building, for now the SHM system will provide red-yellow-green alarms for on-site security and emergency response team to take appropriate actions after an earthquake. Alerts with automatically-generated reports displaying the building response status Figure 6 and will be sent to the designated officials to support their emergency response decisions. Moving forward, onsite response team members should be trained on the plan and periodic annual drills (similar to fire alarm testing).

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. Experiences gained through projects such as those mentioned 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 EMP Intelligent Building.
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.

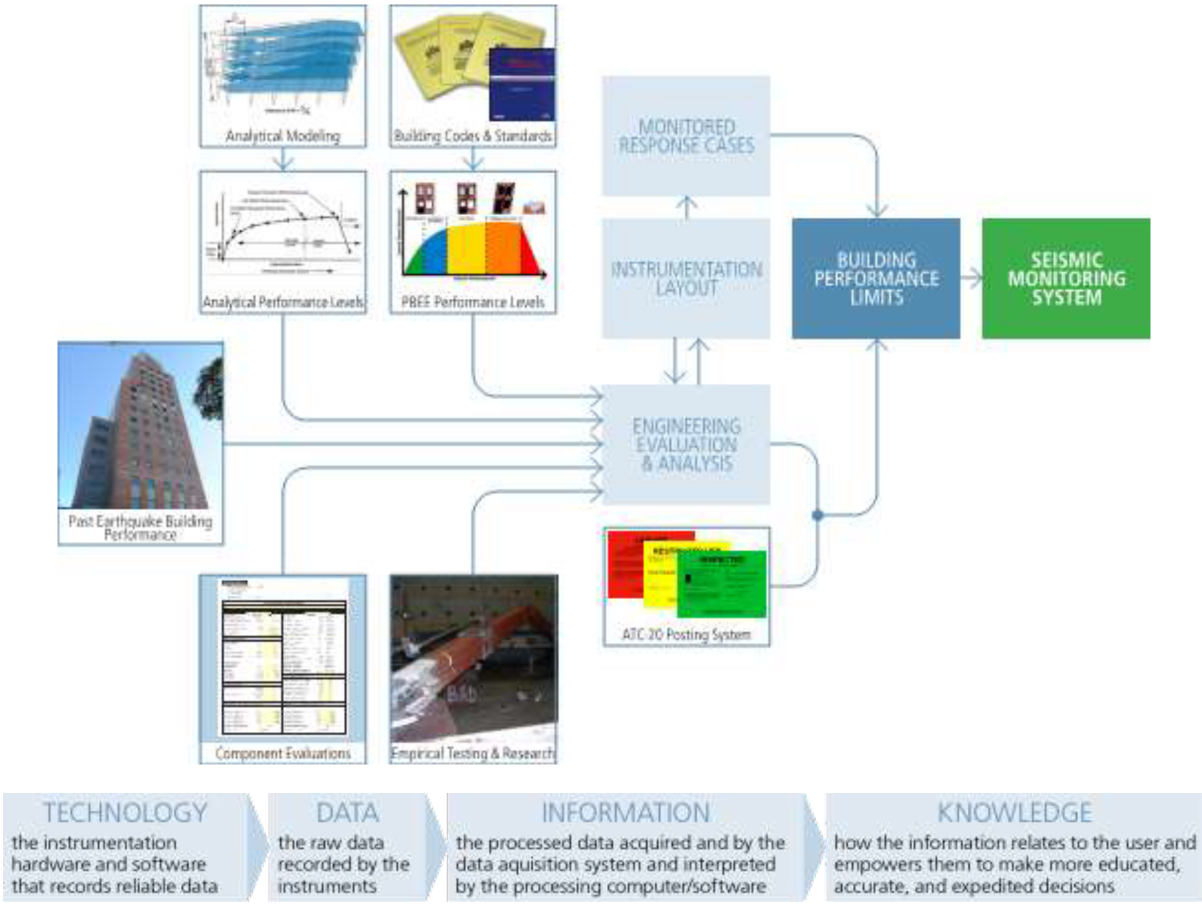

Figure 5: Conceptualization of OASIS and Response Planning integration [13]

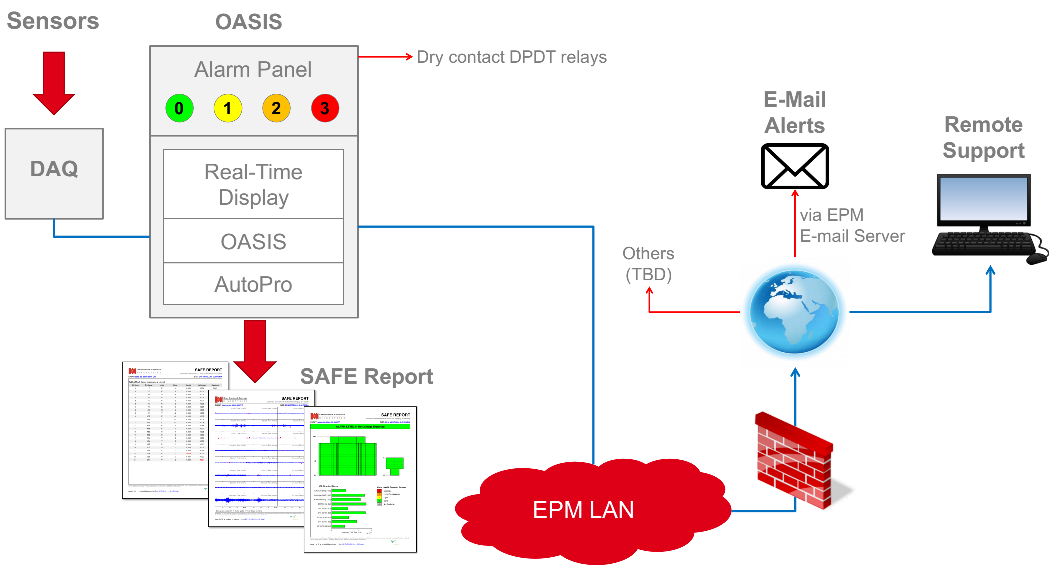

Figure 6. EPM's Intelligent Building Data/Information Flow

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