IMPLEMENTACIÓN DE MONITOREO ESTRUCTURAL Y CONCEPTOS DE DISEÑO POR DESEMPEÑO PARA LA CONTINUIDAD DE OPERACIONES POST-SISMO DE TORRE GLORIETA INSURGENTES

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RESUMEN

En general, las estructuras de importancia alta como son hospitales, centros de operaciones o emergencias, de gobierno, instalaciones militares, instituciones o centros financieros, centrales nucleares y edificios altos, no pueden ser fácilmente evacuados inmediatamente después de ocurrido un sismo. Las evaluaciones detalladas sobre las condiciones de seguridad estructural para dictaminar habitabilidad y continuación de operaciones requieren tiempo valioso que implican pérdidas de productividad, económicas y de otras índoles por la interrupción de las actividades normales en las edificaciones.

La intensidad que imprime el evento sísmico en la edificación puede medirse y establecer niveles de alarma que diferencien el nivel de respuesta a implementar ante la emergencia sísmica. La toma de decisiones de los responsables de protección civil y seguridad estructural son difíciles de establecer sin la información sobre los efectos del sismo en las estructuras, en particular en los minutos posteriores a la emergencia, derivándose en muchas ocasiones en acciones desfavorables como son aumentar el pánico generalizado, lesiones a los usuarios y pérdida por el paro en operaciones dentro de los edificios.

Recientemente, en el edificio "Torre Glorieta Insurgentes" se instaló un sistema de monitoreo del desempeño estructural basado en instrumentos de registro sísmico de alta confiabilidad que además incluyen un programa automatizado de respuesta post-sismo orientado a incrementar sustancialmente la confiabilidad en la toma de decisiones relacionadas con la protección civil, minimizar las pérdidas por paro en las actividades normales de operación en las edificaciones, así como generar información casi inmediata de alta confiablidad sobre el desempeño estructural y sus posibles daños. El sistema cuenta con sensores que registran en tiempo real la respuesta estructural ante el sismo, mediante el uso de acelerómetros distribuidos en áreas claves de la estructura para la determinación de valores de distorsión entrepiso, considerado como el parámetro mejor asociado al desempeño y nivel de daño. Además, es posible relacionar la información obtenida con niveles de desempeño estructural preestablecidos como son: Ocupación Inmediata, Protección de la Vida y Prevención de Colapso. En este trabajo se provee detalles acerca del sistema de monitoreo, su implementación, así como ejemplos del tipo de reportes generados.

ABSTRACT

In general, essential structures such as hospitals, operations and emergency centers, government facilities, military installations, financial centers, nuclear power plants and tall buildings, cannot easily evacuate immediately after an earthquake. Detailed safety assessments to reoccupy and resume operations require valuable time which can lead to financial and other type of losses due to downtime resulted from disruption of normal activities at such buildings.

The intensity that a seismic event could impose on buildings can be measured and levels of alarm that differentiate the level of response required upon such an emergency can be implemented. The decision making of the responsible civil protection and structural safety personnel are difficult without information of the effects that the seismic event impose on the structure, in particular during the few minutes after the seismic emergency, and can have dire consequences such as panic-related injuries, significant loss due to unnecessary downtime, etc.

Recently, "Torre Glorieta Insurgentes" was installed with a structural performance monitoring system based on highly reliable seismic instrumentation which also includes an automatic post-earthquake response program

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oriented to substantially increase the confidence in civil protection decision making process, minimizing losses due to downtime, as well as delivering real time generation of information on the performance of the structure and potential of damage. The system is composed of sensors which record real time response of the structure due to earthquakes, using accelerometers distributed in key areas of the structure to determine interstory drift ratios, which is considered as the structure response parameter that better correlates with performance and potential of damage. Also, it allows the correlation of the obtained information with pre-stablished levels of performance such as: Immediate Occupancy, Life Protection, and Collapse Prevention. This paper provides details about the monitoring system and its implementation, as well as the types of generated reports.

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 of the last revision of the Reglamento de Construcciones para el Distrito Federal which requires structures categorized as Grup A Case 3 and Subgrup B1 Case 6 to be instrumented. 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 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 “Torre Glorieta Insurgentes” recently was installed system.

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, 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.
In Mexico as well, Proteccion Civil has proposed guidelines for post-earthquake evaluation of structures.
However, often these 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 Torre Glorieta Insurgentes, the building has been equipped with permanent structural health monitoring system. The primary goal of these systems is to empower civil protection decision making process, as well as delivering real time generation of information on the performance of the structure and potential of damage, useful for making informed building occupancy decisions and avoid unnecessary evacuations similar to those that have occurred in past earthquakes, 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.

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.

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

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.

Se registra fuerte sismo de magnitud 7.2 con epicentro en Pinotepa Nacional

Usuarios en redes sociales informaron que este sismo se sintió en al menos nueve entidades del país

Por Miguel Ángel Bravo
Viernes 16 de febrero de 2018, a las 18:13

REPORTE DE PROTECCIÓN CIVIL NACIONAL

- **Chiapas:** Se reporta que fue percibido de manera moderada y con activación de protocolos de evacuación.
- **Estado de México:** Activación de protocolos y revisión de inmuebles. El Servicios de Urgencia del Estado de México (SUEM) desplegó el protocolo de supervisión para este tipo de contingencias, tanto en escuelas, como en oficinas y hospitales, sin reporte de afectaciones. En lo que respecta a las más de mil 200 unidades médicas de primer nivel y los 78 hospitales de la red a cago del ISEM, éstos se reportan sin daños, de manera preliminar.
- **Pinotepa Nacional, Oaxaca:** Reporta afectaciones sin cuantificar, en proceso de evaluación. Percibido fuertemente.
- **Guerrero:** El Centro Estatal de Alertamiento informa que el sismo fue percibido fuerte en los municipios de la región Costa Chica, Norte, Montaña, Centro, Acapulco, de moderado a fuerte en las regiones Costa Grande y Tierra Caliente. Al momento sin reporte de daños.
- **Ciudad de México:** Percibido de moderado a fuerte, evacuaciones preventivas, activación de protocolos y revisión de inmuebles.

- **Ciudad de México:** Percibido de moderado a fuerte, evacuaciones preventivas, activación de protocolos y revisión de inmuebles.

Figure 2. Spread panic and unnecessary evacuations in Mexico City due to the 7.2 magnitude Pinotepa Nacional earthquake of February 16, 2018
(Source: https://www.publimetro.com.mx/mx/noticias/2018/02/16/vuelve-a-temblar-se-registra-sismo-magnitud-7-epicentro-en-pinotepa-nacional.html)

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

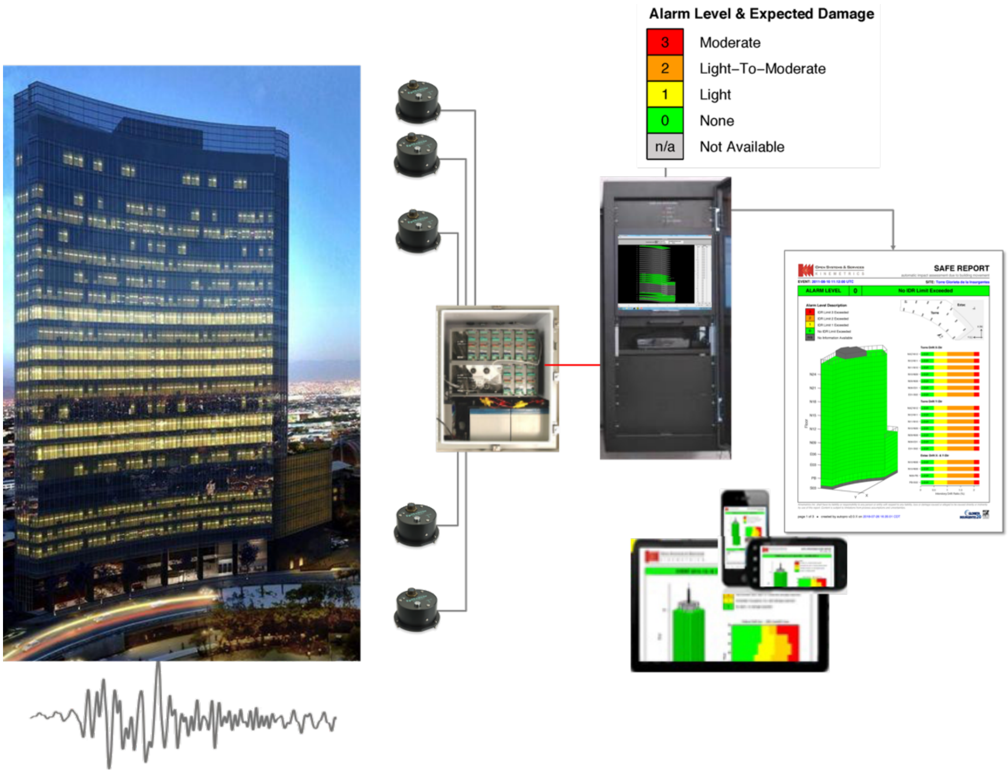

Figure 4. Torre Glorieta Insurgentes structural health monitoring system

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, 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.

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.

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?

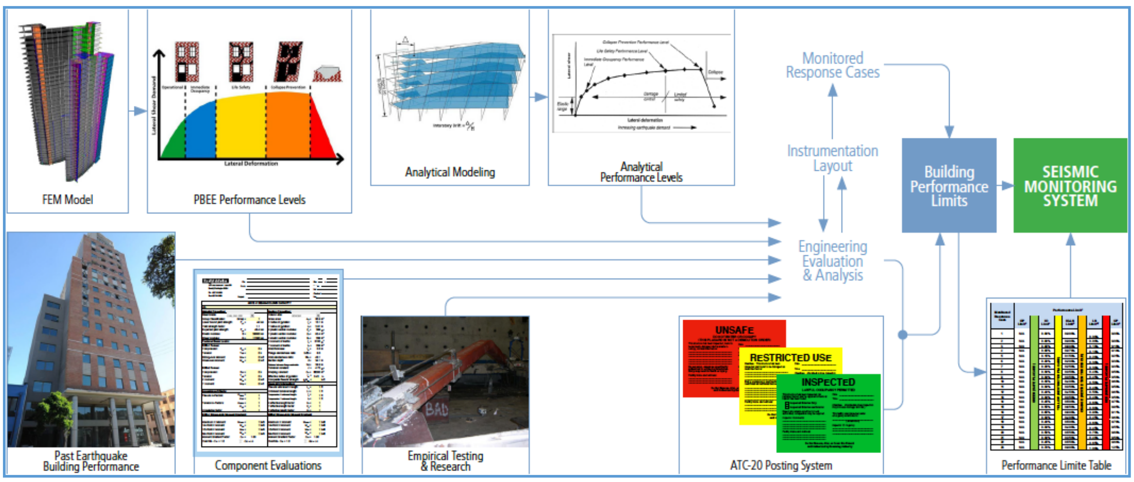

Figure 5. From alarm system to a rapid post-event assessment program, REAP®

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

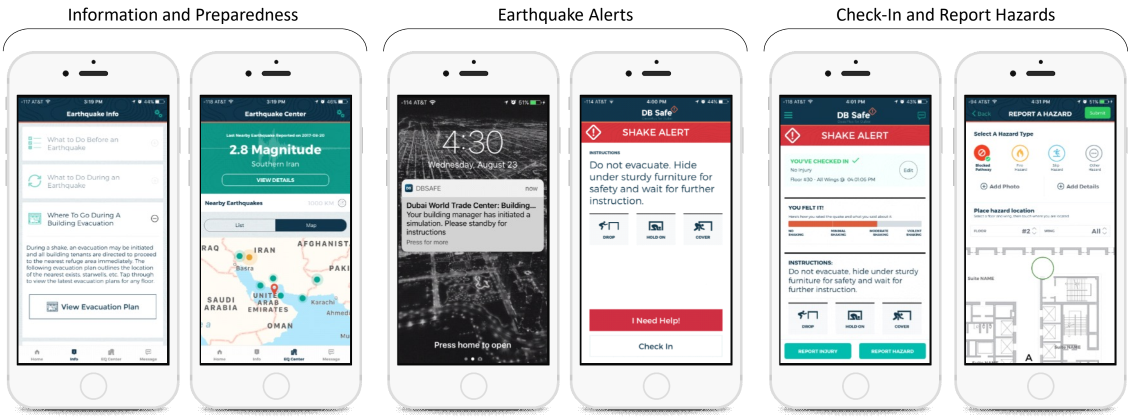

Figure 6. OasisPlus mobile application

TORRE GLORIETA INSUREGENTES

Specifically, the Torre Glorieta Insurgentes Oasis system consists of 24 accelerometers distributed in key areas of the main building and parking structure, this monitors in real time interstory drift ratios and upon the occurrence of an earthquake will provide alarms based on pre-stablished levels of performance such as: Immediate Occupancy, Life Protection, and Collapse Prevention. The system will deliver a SAFE Report detailing these results in a form of PDF report and the alarm level will be broadcasted via the Building Management System and displays throught the building for Civil Protection purposes.

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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