"SHAKEMAP®" FOR BUILDINGS

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Abstract

You should not be able to feel the building you are in right now moving. If you can, it most likely means something big and terrifying is happening (and you are no longer reading this). Distress comes fast and is from not knowing what is going on or how severe it is going to get. Earthquake early warning systems will certainly help minimize this, but the shaking will still happen and people are left asking; now what? Is my building OK? Should I evacuate? And if you did evacuate, when is it OK to re-enter and resume operations? Everyone faces this reality immediately after any sizable earthquake.

ShakeMap® by USGS quickly answers the question about how widespread an earthquake's impact is. However, what about the building you are in, or in-charge of? "ShakeMap" for Buildings is the 'tongue-in-cheek' name for a concept that provides an immediate and automatic picture of the expected impact of shaking on an individual building's structural and non-structural systems and the residing occupants. With a single image, it is meant to inform occupants and managers alike about the likelihood of structural and non-structural damage, on how messy each floor will likely be, and how panicked people on each floor are likely to be. Armed with greater situational awareness, building managers can make well-informed decisions and avoid costly and perhaps dangerous, overreactions.

This paper presents a novel concept coined "ShakeMap" for Buildings. Requirements such as instrumentation, real-time monitoring and data processing, graphical visualization, and performance-based earthquake engineering are presented first. A detailed discussion and derivation of the so-called expected impact scale are then provided. The paper concludes with presenting a simulated post-earthquake response report using the new expected impact scale with default values.

Keywords: instrumentation, performance-based earthquake engineering, rapid post-event assessment

1. Introduction

Critical and essential facilities such as hospitals, military installations, and financial institutions, cannot easily evacuate immediately after an earthquake or wait for a detailed safety assessment to reoccupy and resume operations. Post-disaster occupancy decisions are difficult, especially under such stressful conditions, and can have dire consequences if made hastily 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 across areas of low and high seismicity [1].

For enabling better-informed post-earthquake decision-making of essential and critical facilities, there exists a comprehensive commercially available solution [1, 2]. The solution, based on seismic monitoring technology and a suite of engineering services, is well described in the provided references. Here, we only wish to highlight the fact that it is highly customized per client and demands significant investment and recurring resources. Certainly worthwhile for essential and critical buildings, but what about the other ~95% of buildings that may not warrant such a comprehensive solution. And what exactly is required to implement a monitoring solution that successfully enables better-informed post-earthquake decision-making? This paper aims to address these questions and present a novel concept inspired by the United Stated Geologic Survey (USGS) ShakeMap®, but designed for individual buildings. “ShakeMap®” for Buildings is the ‘tongue-in-cheek’ name for this concept that provides an immediate, automatic picture of the expected impact of shaking on a building's structural and nonstructural systems as well as contents and the residing occupants. We now call this concept whole-building shake impact.

Knowing the expected level of damage distributed throughout the building would certainly empower emergency managers and decision-makers who often rely on limited resources. Furthermore, knowing the expected state of stress of the occupants would lead to better organizational communication and effectiveness. Human experience in an earthquake is known to vary dramatically from floor to floor of the building– most likely because the dynamic response of a structure typically amplifies an earthquake’s ground motion. In fact, clients have shared with us instances in which those on the ground or lower floors of a building did not perceive that an earthquake occurred, while some on the upper floors experienced a moderate level of shaking. Regrettably, building control rooms are often tucked away in basements whereas VIPs who may demand immediate assurance are often at the top.

2. Background

Several circumstances have facilitated the need for the proposed tool. These include. 1) the advancement of communication technology and smart phones, 2) the large quantity of instrumented buildings, 3) a heightened sense of public awareness on existing earthquake hazards, and 4) the demonstrated success of ShakeMap as a public information tool.

2.1 Building Monitoring for Earthquakes

Beginning in the 1970’s, buildings were instrumented with strong-motion accelerometers for the sole purpose of cataloging structural response to damaging and potentially damaging earthquakes [3, 4]. As shown in Fig 1, there are over 300 buildings in Los Angeles, CA instrumented under various strong-motion instrumentation programs [3, 4]. Engineers and seismologists 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 [5]). Over time, the cost-bearing public (owners and occupants) indirectly benefit from these programs by owning and residing in safer structures. However, there is now opportunity for owners and occupants to benefit directly and immediately from the earthquake monitoring technology already installed in many of their buildings.

Although the concept of using sensor data to the direct benefit of building owners has been considered in the past [6], in the opinion of the authors, it has only recently been implemented as a holistic, commercially viable solution. We attribute this to a combination of strategic academic and industrial partnerships, advantageous commercial opportunities, and a shared growing body of knowledge and experience on the topic. As mentioned previously, essential and critical facilities have been most of the early adopters. However, our hope is that the tool presented here, in conjunction with facilitating circumstances may make the use of these data by their owners more widespread. Consider the list of pre-1976 non-ductile concrete buildings identified in Los Angeles, CA released from a 2014 University of California Study [7] that led in part to the 2015 mandatory "retrofit" ordinance. As seen in Fig 1, there is considerable overlap between the instrumented and potentially at-risk buildings [8].

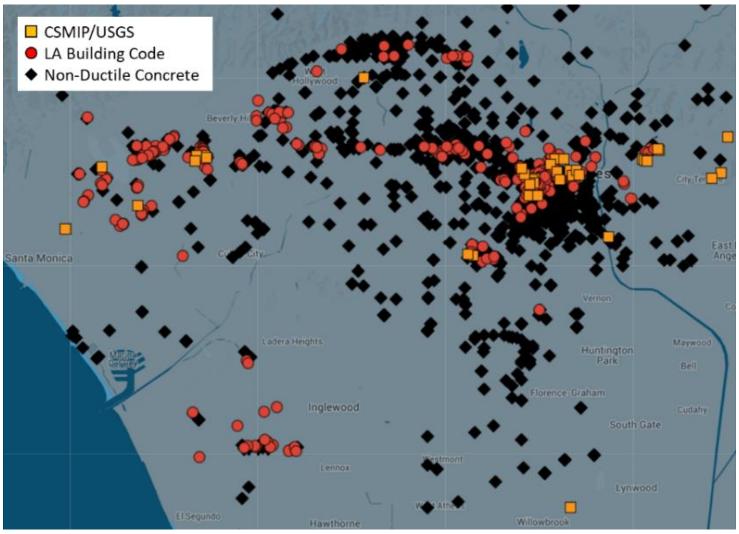

Fig. 1 – Map of Los Angeles, CA showing buildings instrumented under CGS/USGS strong-motion instrumentation program [3, 4], under City of Los Angeles building code requirements, and pre-1976 non-ductile concrete buildings as listed by Los Angeles Times [8]

Additional developments (at least in Los Angeles, CA) adding to the list of facilitating circumstances include the mayor's Resilience by Design document released in 2016 and the US Resiliency Council (USRC) earthquake building rating system. Finally, the advent of media use of ShakeMap speaks to a forward-thinking community ready to utilize all the tools available to help curb the existing earthquake hazard and inject resilience where possible – it is conceivable that a moderate-sized event, which causes minimal damage, may now result in higher states of panic and/or overreaction.

2.2 USGS ShakeMap

As described on the USGS website [9], "ShakeMaps provide near-real-time maps of ground motion and shaking intensity following significant earthquakes. These maps are used by federal, state, and local organizations, both public and private, for post-earthquake response and recovery, public and scientific information, as well as for preparedness exercises and disaster planning."

In the authors' opinion, widespread public use of ShakeMap is an incredible success story. Any publicity given to the advancement of earthquake hazard mitigation is welcome, especially since many news agencies still use a drum recorder as their go-to-graphic for earthquake related stories. As seen in Fig 2, the beauty of ShakeMap is that it can convey very useful and consumable information in a timely manner. Additionally, past earthquakes have shown pockets of concentrated damage away from the epicenter and unlike other information released and reported on (i.e., magnitude and location), ShakeMap can capture this [11].

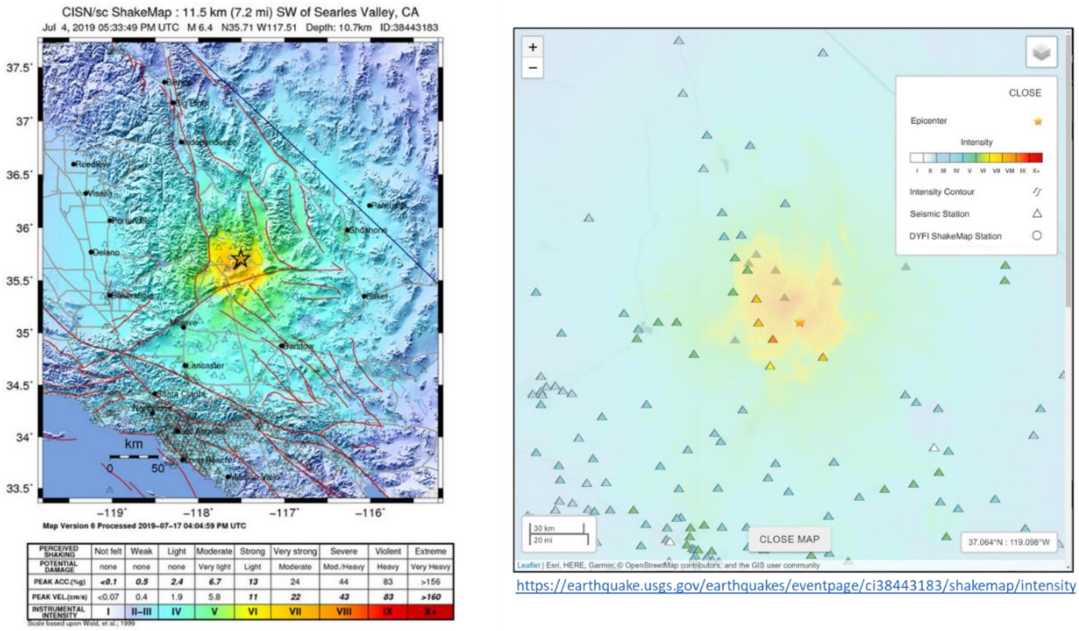

Fig. 2 – Example ShakeMap image and expanded view of participating ShakeMap stations for the M6.4 2019 July 4 Searles Valley Earthquake [9]

However, when it comes to assessing a single point of interest, like a building, ShakeMap may not be the best tool available for quantifying impact. This is because the estimate of shaking at any particular grid point is based on spatial interpolation of measured ground motions and site-dependent corrections. This leads to ShakeMap values being quite different from those measured directly by a strong-motion sensor at the strong-motion sensor location see Fig 2. Moreover, buildings are in fact three-dimensional. Thus, there is a need, for those buildings that can benefit from knowing immediately what the impact could be and how it is distributed within. Prior to describing the proposed tool, we provide next a hard-won list of requirements for deploying such a solution.

3. General Requirements

Experience from instrumenting hundreds of buildings over the past 50 years has led to a comprehensive list of requirements needed to implement a solution that is both valuable to the building owner and commercially viable. In total, there are six requirements identified as illustrated in Fig 3.

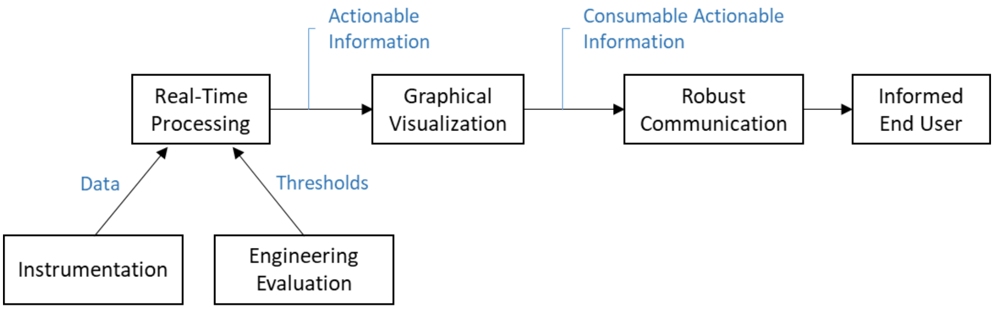

Fig. 3 – Data/information flow through the six required facets for successful implementation of a monitoring solution for better-informed post-earthquake decision-making

3.1 Instrumentation

Instrumentation (i.e., sensors and data acquisition systems) acquires building response data. These data are considered the foundation of the solution in that it is one of the most basic elements needed to build upon, but also that it is mostly unusable to building owners/occupants, except for those willing to get a bit dirty.

Sparsely instrumented buildings can utilize interpolation schemes to fill in gaps in the vertical stack of sensors. Tall buildings are generally simpler to instrument than short-but-large buildings that may in fact be several seismically independent structures. Hospitals, for example, tend to be a conglomerate of different buildings of different vintages continuously being remodeled. The tool proposed here is considered for single building only.

Because instrumentation and hardware in particular, is the most visible initial upfront cost, it tends to be described in literature as needing to be inexpensive. However, history of long-term projects have shown that low quality hardware inevitably leads to inoperable systems or unusable data in a relatively short time. Because building lifetimes are measured in decades and earthquake risk in centuries, it stands that the most important aspect (in terms of return on investment when selecting instrumentation is reliability.

3.2 Engineering Evaluation

An engineering evaluation of structural and non-structural systems is required for understanding system capacities to move and, more importantly, how much movement is expected to cause damage. Multi-level thresholds or scales have been, and are still, the key converter of data into more meaningful and actionable information such as alarms. The level of engineering effort required depends on several factors such as building size and use, client tolerance to risk of false alarms, and of course budget. It can range from advanced nonlinear analyses using finite element models to simple lookup of design values. Different level of approaches are explored a bit further in section 4 for both structural and nonstructural systems.

3.3 Real-Time or Automatic Processing

In order to turn raw data into something usable, a few things are necessary. First, signal processing is required to extract and validate data. High-level processes include filtering, numerical integration, computing interstory drifts, and checking exceedance criteria. This, in fact, is the bulk of what most structural health monitoring (SHM) software packages do – compute important engineering parameters and issue alarms upon user-defined exceedance thresholds. Fancier packages can do more elaborate processing to output more technical parameters (e.g., modal properties and other damage metrics), but they tend to stay within academic communities probably due to lack of market demand or insufficient commercial support.

3.4 Graphical Visualization

Having meaningful and actionable information is key, but is still not the result that most decision-makers (typically non-engineers) are looking for. What everyone inevitably wants to know right after an earthquake is how bad it was – in other words; what is the impact. This is where effective graphical visualization adds value. It turns the meaningful actionable information (such as a table of alarm values) into something easily consumable (such as a heat map). Of course, a simple red/yellow/green stoplight is easy to consume, but it is not terribly useful. A particularly relevant analogy is earthquake magnitude. Everyone knows what the Richter scale is, more-or-less, but knowing an earthquakes magnitude is not enough to say how bad shaking was at any particular point of interest. ShakeMap has stepped into that role for quickly visualizing the regional impact of an earthquake.

3.5 Robust Communication

The easily consumable actionable information now needs to be in the hands of those who need it. Robust communication is the fifth required tenet to successful implementation of a monitoring solution for better-informed post-earthquake decision-making. As simple as it is, it is also the most fragile component. For example, wireless technology continues to tempt us away from expensive bulky cabling, but those charged with maintaining most of the world's structural monitoring systems know too well the true cost of lost connections, especially in remote or hard to reach locations. Imagine repeatedly needing to access a sensor that just happens to be installed above a hospitals' 24-hour Emergency Room - an unfortunate, yet common scenario. In this case, a permanently tethered set-it and forget-it solution really is the only viable one.

3.6 Forward Thinking Management

Forward-thinking ownership and management is probably the most important yet allusive of the six requirements. It also involves dedicated onsite personnel and training on how to use the system, receive the information, and enact proper plans. Here is another area in which simple graphical visualization adds considerable value. It is also the subject of the following section.

4. Whole Building Expected Impact

The term "whole-building" was coined in an attempt to broaden our scope beyond damage to structural systems. Our goal is to provide an expected impact on everything that is important to know about immediately after an earthquake. In this way, whole building can include structural and architectural systems, nonstructural systems and general contents, and of course the occupants.

At the same time, following the lead by ShakeMap, we still seek a single concise image that conveys whole-building expected impact. Our approach is to first define a performance range with corresponding threshold values for each impact type and then combine them all into a single multi-level alarm scale, referred to as the Expected Impact Scale, which can then be used to create 3D heat map images of the building.

4.1 Structural Systems

Structural systems refer to the lateral force resisting system, which can be one or a combination of several different types. For typical reinforced concrete or steel frame buildings, peak interstory drift (PID) is the engineering demand parameters that best indicates the potential for structural damage [11, 12].

PID limit thresholds are often related to performance design levels such as Immediate Occupancy (IO) Life Safety (LS), and Collapse Prevention (CP) as described in documents such as ASCE 41 [13]. Typically, performance levels are associated with target damage states often linked to green/yellow/orange/red (and sometimes blue) coloring. Fig 4 depicts this concept by discretizing a conceptual demand-to-deformation relationship into several performance levels.

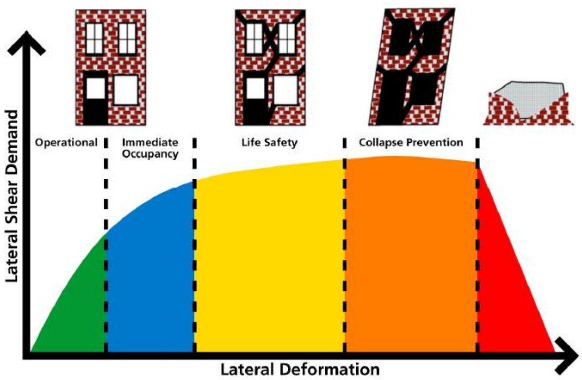

Fig. 4 – Building performance levels as function of lateral deformation.

4.1.1 Detailed Approach

For a given building, the state-of-the-art approach for defining structural performance response thresholds, or PID limits, is through advanced non-linear finite element model analyses using Performance-Based Earthquake Engineering (PBEE) evaluation standards such as ASCE 41 [13]. For example, a pushover analysis can yield a set of PID limits associated with IO/LS/CP that will vary floor-to-floor and in each horizontal direction. The limits can then be arranged to match a buildings' instrumentation layout. The resulting scale is used to color floors based on exceedance of the specified drift limits. For practical reasons, CP limits are omitted in favor of more granularity within lower performance levels. This is because at collapse level, the situation is obvious and first responders take charge.

The detailed approach is the preferred method for existing comprehensive monitoring solutions, but for our purpose, with aims of more widespread use for more common building stock, we seek a simplified approach.

4.1.2 Simplified Approach

In the absence of a detailed engineering evaluation, structural damage thresholds can be obtained from the documented information that supports the HAZUS methodology, specifically the content provided in *Chapter 5 Direct Physical Damage – General Building Stock* of HAZUS Technical User Manual [14], herein referred to as HAZUS Manual. The content described in the HAZUS Manual supports the formulation of probabilistic relationships between varying levels of structural (and nonstructural) damage to ground motion parameters such as peak ground acceleration (PGA). Nevertheless, much can be leveraged for our purpose to define expected structural damage levels directly from interstory drift parameters. Instead of a full engineering evaluation, we can lookup threshold values based on building characteristics such as structural type and height. For example, consider four common structural system types used in high-rise (8 stories or more) construction (see Table 1 first column). For these building types, and assuming a high seismic design level (i.e. post-1975, UBC Seismic Zone 4), we can obtain interstory drift values at the threshold of slight, moderate, extensive, and complete (collapse) damage states from *Table 5.9a Structural Fragility Curve Parameter* of the HAZUS Manual [16]. Similar to Collapse Prevention performance level, we can ignore the fourth damage state because at that point the expected impact is obvious. Table 1 displays the PID limit threshold values for structural damage from HAZUS Manual.

Table 1 – Structural impact threshold values for four common high-rise, high-code building types. Data from Table 5.9a-b of HAZUS-MH Technical Manual [14]

HAZUS Building Type High-Rise (8+ Stories), High-Code	**Drift Ratio at Threshold of Structural Damage**		
	Slight	Moderate	Extensive
S1H: Steel Moment Frame	0.3%	0.6%	1.5%
S2H: Steel Braced Frame	0.25%	0.5%	1.5%
C1H: Concrete Moment Frame	0.25%	0.5%	1.5%
C2H: Concrete Shear Walls	0.2%	0.5%	1.5%

The values presented in Table 1 are appropriate for default threshold limits for structural damage in our expected impact scale and demonstrative purposes. An important distinction in the simplified approach is that drift thresholds are uniformly applied to all floors and in both horizontal directions. Additionally, the HAZUS values do not account for added strength in buildings designed for wind. For larger, more complex or critical installations, a detailed evaluation is always recommended.

4.2 Nonstructural Systems & Contents

Nonstructural systems refer to architectural, mechanical, electrical, and fire protection systems that are installed (i.e., affixed) in and on building structures. The other myriad building "contents" (such as furnishings, equipment, etc.) may not necessarily be affixed to the structure. Nonstructural components are generally grouped as flexible/drift-sensitive or rigid/acceleration-sensitive components based on their dynamic performance and damage susceptibility. Earthquake damage to rigid components (such as floor-mounted mechanical equipment, HVAC, and lighting fixtures) and contents is primarily a function of acceleration where-as damage to flexible components (such as wall partitions, penthouses, and exterior veneer) is more related to interstory drift.

4.2.1 Detailed Approach

Similar to structural systems, performance thresholds for each nonstructural group at each story are ideal. The performance of nonstructural components is directly related to the internal strength of the nonstructural component, the component connections to the structure, the floor accelerations, the dynamic response of the component, and the relative movement between the structure and the component. An attempt to accurately model and analyze the empire of nonstructural systems is as daunting as it is unnecessary. Building codes provide simplified equations that are intended to calculate design forces for nonstructural components in order to meet the specified earthquake performance objectives. ASCE 41 provides nonstructural response design values associated with dynamic response characteristics identified for different nonstructural system components [13]. For example, acceleration thresholds can be based on design values in accordance with nonstructural design equations (e.g., ASCE 41 Eqn. 13-1) but without factors for dynamic amplification or component response modification. These are not needed here because we directly measure the input; peak floor acceleration (PFA). This approach allows PFA thresholds to vary (generally increase) up the height of a building to compensate for the higher demands for which upper level nonstructural systems are designed for. Furthermore, peak spectral acceleration (PSA) thresholds can be developed to inject more granularity (semi-rigid or semi-flexible) in within the acceleration-sensitive group of nonstructural components. For drift-sensitive systems, drift thresholds can be taken directly from ASCE 41 performance levels.

4.2.2 Simplified Approach

Similar to the simplified approach for structural systems, we can again look to HAZUS for a simplified approach for establishing nonstructural damage thresholds. In the HAZUS methodology, nonstructural damage is not building-type specific, and the seismic design level is considered for acceleration-sensitive systems only. PFA (for the same high seismic code design level) and PID thresholds from *Table 5.12 Peak Floor Accelerations Used to Define Median Values of Damage to Nonstructural Acceleration-Sensitive Components* and *Table 5.10 Drift Ratios Used to Define Median Values of Damage to Nonstructural Drift-Sensitive Components*, of the HAZUS Manual [16] are shown in Table 2.

Table 2 – Nonstructural impact threshold values for acceleration-sensitive and drift-sensitive systems. Data from Table 5.12 and 5.10 of HAZUS-MH MR1 Technical Manual [16]

Nonstructural Damage	Slight	Moderate	Extensive
PFA	0.3g	0.6g	1.2g
PID	0.4%	0.8%	2.5%

4.3 Occupant Perception

Human perception is perhaps the simplest of the three building elements to implement. There is no detailed approach because establishing accurate thresholds is too complex due to the nature of human perception to vibrations. There are numerous references and research used for identifying human perception thresholds from dynamic motion, including standards used for evaluating vibration of floors and pedestrian bridges due to human activities, tolerances for vibration-sensitive equipment and activities (e.g. laboratory testing), and vibration levels due to construction activities. However, these standards are primarily oriented around high-frequency vibrations that resonate with vertical structural responses. For earthquake vibrations, the thresholds should be based on human perceptions from lower frequency horizontal vibrations. Here, we can look back to the USGS ShakeMap for a suitable approach toward quantifying human perception of shaking. The ShakeMap scale in Fig 2, developed by Wald, et al [11], as well as others scales used, presents a range of perceived shaking from "Not Felt" to "Extreme", corresponding to the modified Mercalli intensity (MMI) scale [11]. The perceived shaking scale is based on peak ground acceleration and peak ground velocity. For our purposes, the demand parameters will be PFA and PFV (peak floor velocity).

Directly adapting the full range of the ShakeMap scale to buildings is not appropriate for several reasons. Probably most importantly is that a building with a discrete number of floors simply does not warrant the same granularity as a continuous hundreds-of-kilometer square chunk of the earth's surface. For consistency, the occupant perception scale should have the same number of threshold levels as the structural and nonstructural scales. It also stands that the warmer yellow/orange/red colors of strong shaking intensity stay tied to damage for once structural and/or significant nonstructural damage occurs, the impact on human perception is no longer as critical, nor is it solely dependent on motion – things are much scarier when you can easily see damage. Thus, occupant impact colors will be cooler and left of green so that green is the point at which shaking was scary, but everything is OK. It is OK to continue business as usual. Table 3 displays the three threshold values for occupant impact.

Table 3 – Occupant impact default threshold values (data from Worden et al. 2012 [17])

Occupant Perception	Weak motion	Discomfort	Distress
PFV	1.4cm/s	4.7cm/s	9.6cms/
PFA	0.03g	0.06g	0.12g

4.4 Shake Impact Report

The final step is to combine the three different types of impacts into a single scale (see Table 4) in order to create reports with simple heat map images of a building to describe the various impacts from shaking, termed Shake Impact – Fig 5.

Table 4 – Expected impact scale for HAZUS building type S1H (high-code)

NONE no impact expected	**WEAK** motion felt by some	**DISCOMFORT** in some occupants	**DISTRESSED** occupants but no damage	**SLIGHT** structural and/or nonstructural damage	**MODERATE** structural and/or nonstructural damage	**EXTENSIVE** structural and/or nonstructural damage
PFV < 1.4cm/s	PFV > 1.4cm/s	PFV > 4.7cm/s	PFV > 9.6cm/s			
or PFA < 0.028g	or PFA > 0.028g	or PFA > 0.062g	or PFA > 0.12g	PFA > 0.3g	PFA > 0.6g	PFA > 1.2g
& PID < 0.3%	& PID < 0.3%	& PID < 0.3%	& PID < 0.3%	or PID > 0.3%	or PID > 0.6%	or PID > 1.5%

It is important to note that the actual limit values will vary based on building type, design level, and occupant preferences. The logic is such that only one criteria needs to be satisfied in order to reach a given impact state. The exception is in occupant perception where drift limits must also not be exceeded. The structural and nonstructural thresholds share the same severity-based colors (yellow/orange/red) but because single exceedance condition, only the minimum of structural and drift-based nonstructural PID limit is shown. For instance, in our example, slight nonstructural damage limit is PID > 0.4% whereas slight structural damage limit is PID > 0.3%.

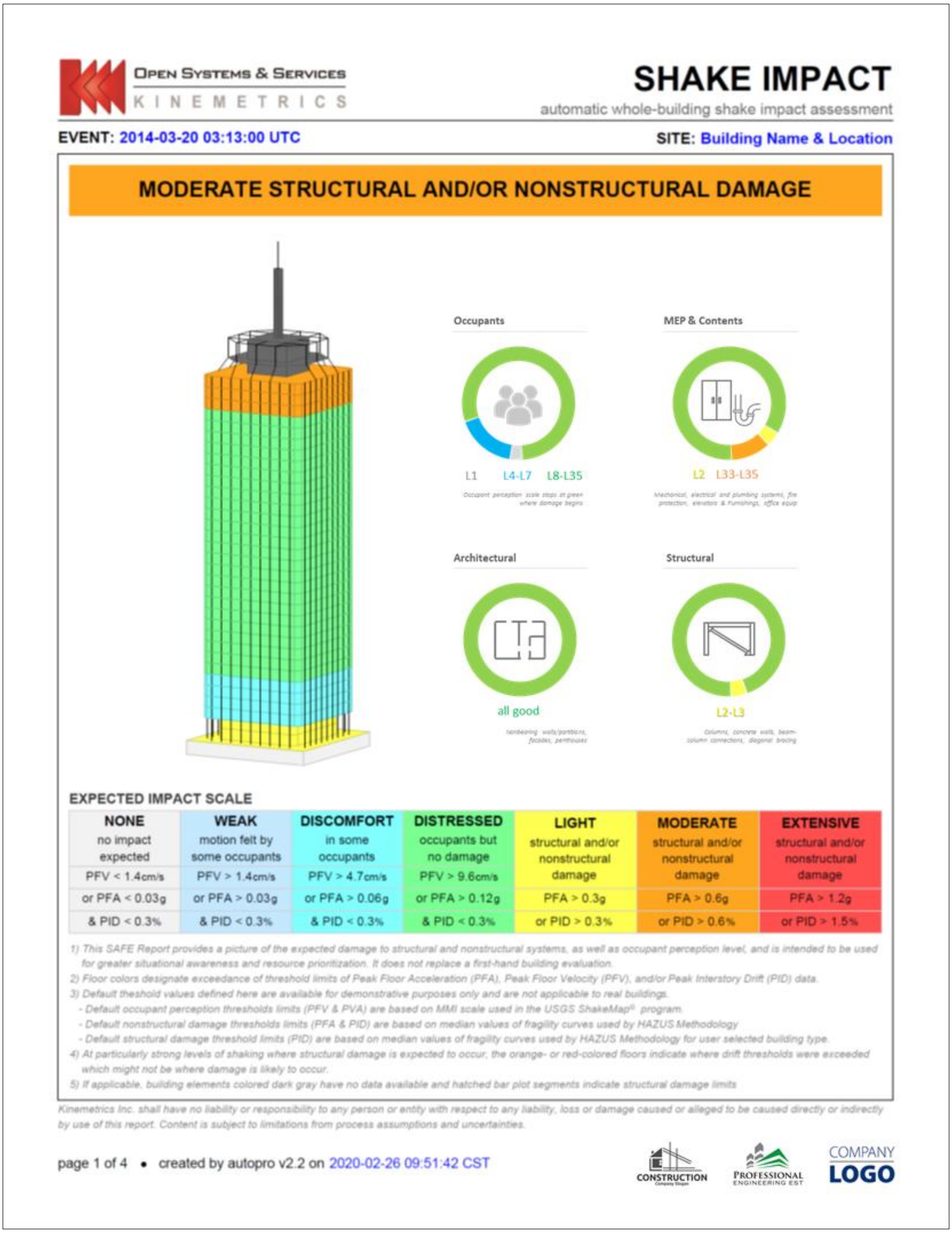

Fig. 5 – Example Whole-Building Shake Impact Report with simulated data [16].

It seems counterintuitive that structural damage would occur before nonstructural, but it is expected in some cases. Architectural systems do not contribute to the lateral force resistance provided by the structural system (or vertical in the case of gravity) but are designed to ride out the deformations without suffering too much damage (i.e. ductility). However, the distinction between architectural and structural systems is generally outside public purview, which may well account for inaccurate initial diagnosis of *unsafe* damage following an earthquake. From this, we can draw one very important conclusion; visible damage to nonstructural systems is not an indicator of structural damage likewise, the absence of visible damage to nonstructural systems does not preclude the existence of structural damage. The shake impact report provides an x-ray of sort into the different types of damages that could be observed.

The expected impact scale has been implemented in an automatic processing and reporting tool that produces reports a few seconds after an earthquake [16]. An example report for a demo building is displayed in Fig 5. It is not a representation of an actual building or real data. The report in Fig 5 has several pieces to call out. At the bottom is the expected impact scale identical to Table 4 but with some additional notes. The 3D building heat map with the floors colored per maximum impact level is on the left. The horizontal bar on at the top is the maximum expected impact level. Finally, the two-by-two circular graphic on the right illustrates the breakdown of impact on the different types. For reference, examples of each type are also provided.

Thus, we have a relatively simple image of a building immediately available to building owners/managers that clearly indicates the expected impact on the building's structural and nonstructural systems, as well as on the occupants. In fact, Fig 5 is an executive summary or cover page to the full report which subsequent pages will contain information that is much more technical and meant for engineers.

There are a few caveats worth noting. The location of a given exceedance does not necessarily coincide with the likely location of structural damage. For example, an exceedance of an upper story structural drift threshold will result in that upper story colored per the expected impact level. However, depending on the building structural systems, damage could likely be concentrated at the base where an exceedance may not have occurred. One possible explanation for this discrepancy is that damage is local phenomena and the rigid floor motions measured are global responses. The relationship between these two is not straightforward. Additionally, design-based thresholds have inherent assumptions. Most notable is that the building is constructed exactly according to plan. The intent of Shake Impact is to provide greater situational awareness and resource prioritization. It does not replace first-hand building evaluation.

6. Conclusions

The need for a novel post-earthquake reporting tool similar to USGS ShakeMap, but for individual buildings was presented citing several circumstances. Similar yet more comprehensive solutions exist, but are adopted mostly by essential and critical facilities.

Six requirements for successful implementation of comprehensive monitoring systems include instrumentation, engineering evaluation, real-time/automatic processing, graphical visualization, robust communication, and forward thinking ownership/management.

Development of an expected impact scale facilitated a single image to convey the impact of shaking on a building's structural and nonstructural systems as well as on the occupants. Default threshold values were defined utilizing key research within the HAZUS methodology and USGS ShakeMap. The culmination of this work; the Shake Impact report presented in Fig 5, provides an automatic snapshot of the impact of shaking on the different types of damages that could be observed. The intent of Shake Impact is to provide greater situational awareness and resource prioritization. It does not replace first-hand building evaluation.

7. Acknowledgements

The authors would like to acknowledge the many people involved in several projects over the past 10-plus years that ultimately led to the conception and realization this papers subject matter. We thank the Abu Dhabi Municipality, Dr. Zoran Milutinovic (who coined the term "ShakeMap for Buildings"), Dubai Municipality, Dr. Kamal Mohamed Atiya, Ms. Eman Ahmed Al Khativi Al Falasi, and many of our colleagues at Kinemetrics and Reid Middleton.

8. References

[1] Skolnik DA, Ciudad-Real M, Swanson DB, Bishop E (2017), "Improving Business Continuity for UAE Buildings Using SHM and PBEE-Based Rapid Evaluation", Proceedings, 16th World Conference on Earthquake Engineering, Santiago, Chile.

[2] Swanson DB, Lum LK, Martin BA, Loveless RL, Baldwin KM (2011) Rapid Evaluation and Assessment Program (REAP) – Innovative Post-Disaster Response Tools for Essential Facilities. 2011 *EERI Annual Meeting*, San Diego, CA, 2011

[3] State of California SMIP (2017), http://www.conservation.ca.gov/cgs/smip/, Retrieved 21-December 2017, USA.

[4] USGS NSMP (2017), http://earthquake.usgs.gov/monitoring/nsmp/, Retrieved 21-December 2017, USA.

[5] Goel RK and Chopra AK (1997), "Period Formulas for Moment-Resisting Frame Buildings", Journal of Structural Engineering, vol. 123(11), pp. 1454-1461, USA.

[6] Celebi M, Sanli A, Sinclair M, Gallant S, Radulescu D (2004), "Real-Time Seismic Monitoring Needs of a Building Owner-and the solution: A Cooperative Effort", Earthquake Spectra, vol. 20(2), pp. 333-346, USA.

[7] Moehle J, (2013) Concrete Coalition (list released to Los Angeles Times)

[8] Older concrete buildings in Los Angeles, Los Angeles Times (2014), https://graphics.latimes.com/la-concrete-buildings\ , Retrieved February 2016, USA.

[9] USGS ShakeMap® (2020), https://earthquake.usgs.gov/data/shakemap/, Retrieved 18-January 2020, USA.

[10] Wald D, Quitoriano V, Heaton T, Kanamori, Scrivner C, Worden B (1999) "TriNet 'ShakeMaps': Rapid Generation of Peak Ground Motion and Intensity Maps for Earthquakes in Southern California", Earthquake Spectra, vol. 15(3), pp 537-555, USA

[11] Naeim F, Hagie S, Alimoradi A, and Miranda E (2005) "Automated Post-Earthquake Damage Assessment and Safety Evaluation of Instrumented Buildings", JAMA Report Number: 2005-10639

[12] Skolnik DA and Wallace JW (2010), "Critical Assessment of Interstory Drift Measurements". ASCE Journal of Structural Engineering, vol. 136(12), pp. 1574-1584, USA.

[13] ASCE/SEI 41-13, 2014, Seismic Rehabilitation of Existing Buildings, prepared by the Structural Engineering Institute of the American Society of Civil Engineers, Reston, Virginia.

[14] HAZUS-MH Technical User Manual, Chapter 5 Direct Physical Damage – General Building Stock.

[15] Worden CB, Gerstenberger MC, Rhoades DA, and Wald DJ (2012). Probabilistic relationships between ground-motion parameters and modified Mercalli intensity in California, Bull. Seismol. Soc. Am. 102, no. 1, 204–221.

[16] AutoPro, (2018), Kinemetrics Inc. https://kinemetrics.com/wp-content/uploads/2017/03/AutoPro-Report-Brochure.pdf

