Applications of Smartphone Seismic Data for Rapid Structural Health Assessment

Sarina Patel, Qingkai Kong, Selim Gunay, Richard Allen

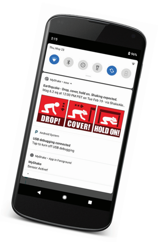
S53G 0546

A Smartphone Seismic Network

The citizen science app, MyShake, represents a new source of global seismic data that can be provided with much higher density sampling than a traditional seismic network and at a relatively low cost. Because phones are most frequently located in buildings, the signal recorded by the on board accelerometer during an earthquake includes structural response information in addition to ground shaking. This work explores the capabilities of MyShake as a remote damage detection tool within the field of structural health monitoring.

- West Coast ShakeAlert targets a station spacing of 10-40 km[1]
- MyShake in San Francisco would have 0.15 km station spacing if just 0.1% of adults ran the app[2].

Now delivering public ShakeAlert earthquake early warning in California!



Every download increases public safety, through early warning, intensity reporting, and other hazard research applications, such as remote structural damage detection for the buildings where MyShake users live and work.

About MyShake

- **MyShake is a citizen science app** that has been freely available around the world since 2016. Since then, the app has been **downloaded nearly 900 thousand times.**

- **Event Detection:** MyShake monitors a smartphone's on board accelerometer and uses a two-fold machine learning discriminator (using frequency, amplitude, and cumulative absolute velocity) to distinguish between ordinary motion and earthquake signals. When MyShake detects earthquake-like motion, it records 5 minutes of data (1 min before the trigger and 4 min after) and sends it to a secure server for further analysis. **MyShake has detected over 1000 earthquakes worldwide that have been confirmed by a seismologist.**

- **Crowd-sourced early warning:** By monitoring the proximity and timing of multiple phone triggers in real time, MyShake can be used for earthquake early warning in parts of the world where a traditional seismic network isn't feasible

- **Public ShakeAlert in CA:** Using rapid notifications, MyShake delivers official ShakeAlert early warning to the public faster than any other available delivery mechanism

- **Experience Reporting:** Users can report their experience of earthquakes within the app, building crowd-sourced, real-time damage estimations

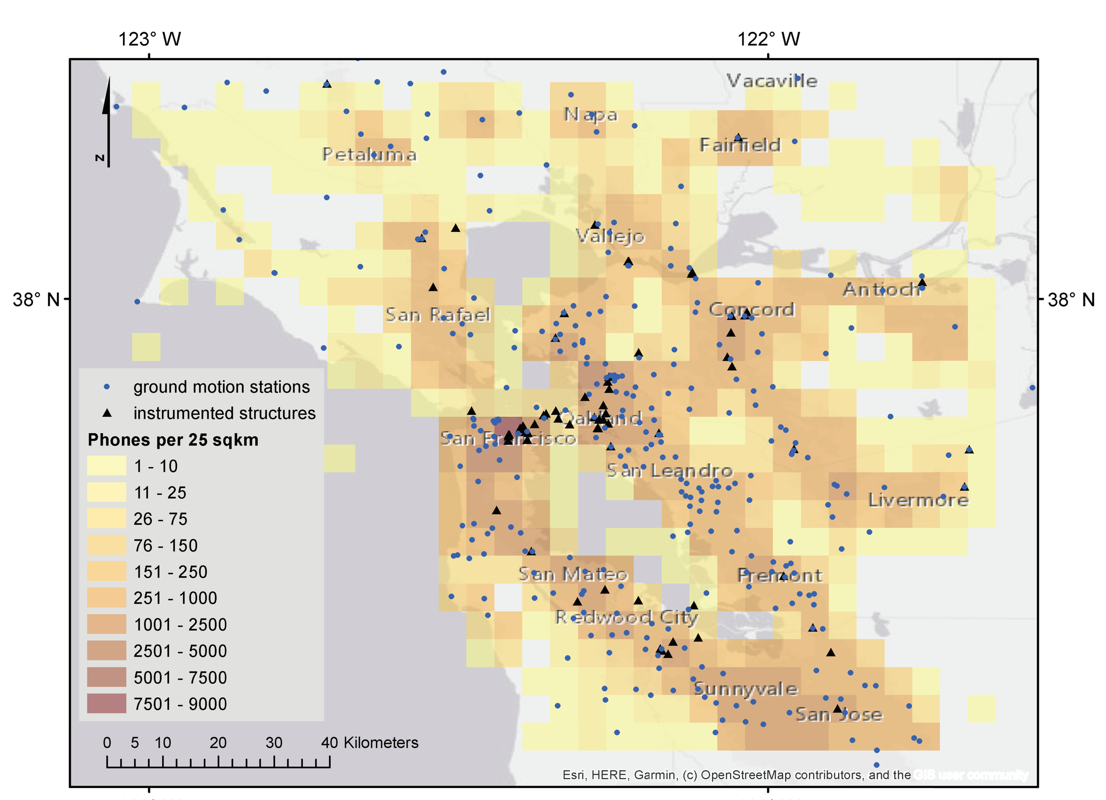


Figure 1: A map of the density of phones running MyShake in the Bay Area since the public alert roll-out in late October of this year. For comparison, permanent stations (free field in blue circles and structures instrumented by the Center for Engineering Strong Motion Data[3] in black triangles) are plotted as well. Station density is improved by orders of magnitude when smartphones are used as sensors.

Motivating Questions

- What conditions are necessary to allow MyShake to be utilized for Structural Health Monitoring (SHM)?
- What are the most useful structural health parameters that can be extracted from MyShake data?
- What variability should be expected in measurements made with MyShake? Is this variability within the tolerance of reliable damage detection?

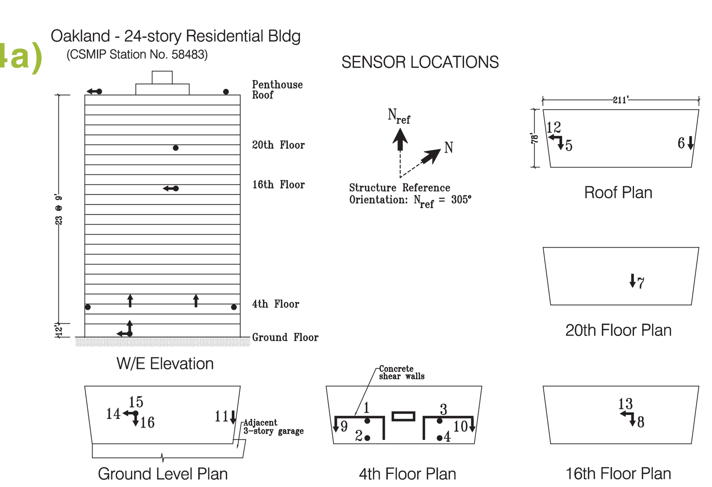
Key Parameters in Structural Health Monitoring

Engineers derive various empirical parameters from vibrational recordings to determine a structure's state of health. Among the most utilized are **modal frequency** and **inter-story drift ratio**.
Modal frequency can be determined using a single sensor placed nearly anywhere within a building, while inter-story drift requires sensors on multiple floors.

Modal Frequency: Every structure has a fundamental frequency, typically 'ball-parked' as 1/# stories[4]. Damage 'softens' a structure, detectable as a new, permanent drop in the modal frequency.

Inter-story Drift: Structures have a natural limit to how much each floor can laterally displace relative to the one above or below and still retain elastic behavior. When the force on the earthquake is sufficiently large, it can exceed the shear strength of the structure, resulting in non-linear behavior, e.g. damage to or weakening of the lateral supports[7].

(4a)



(4b)

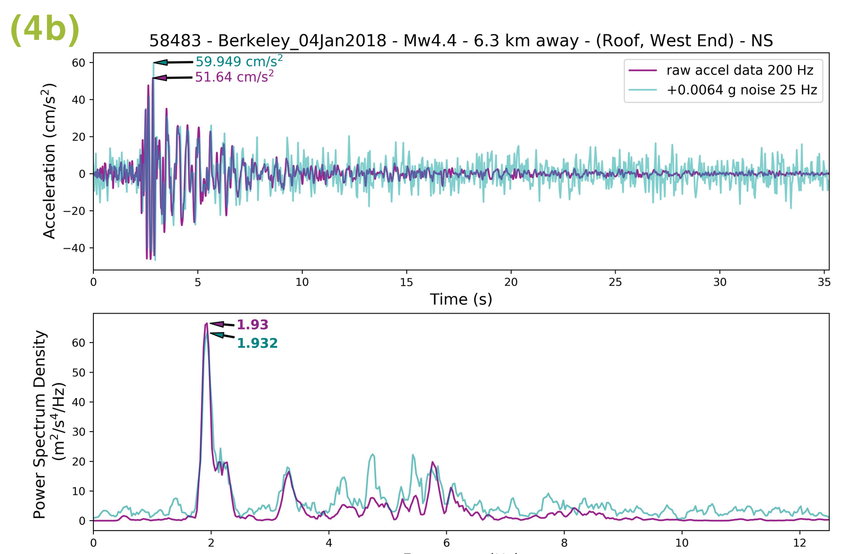


Figure 4a: Floor plans for a 24 story residential building in Oakland, CA, with arrows to indicate the location and orientation of installed sensors.
(4b) Comparing the raw (violet) CESMD record to one modified to mimic expected MyShake behavior (teal) during a Mw4.4 earthquake in Berkeley, CA. Despite higher noise levels, we are able to extract a clear modal frequency from the MyShake data that matches what is derived from the original high quality CESMD data[3].

$$IDR = \frac{Disp_{floor1} - Disp_{floor2}}{Height\ between\ floors}$$

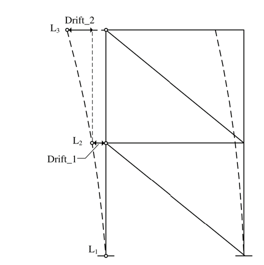
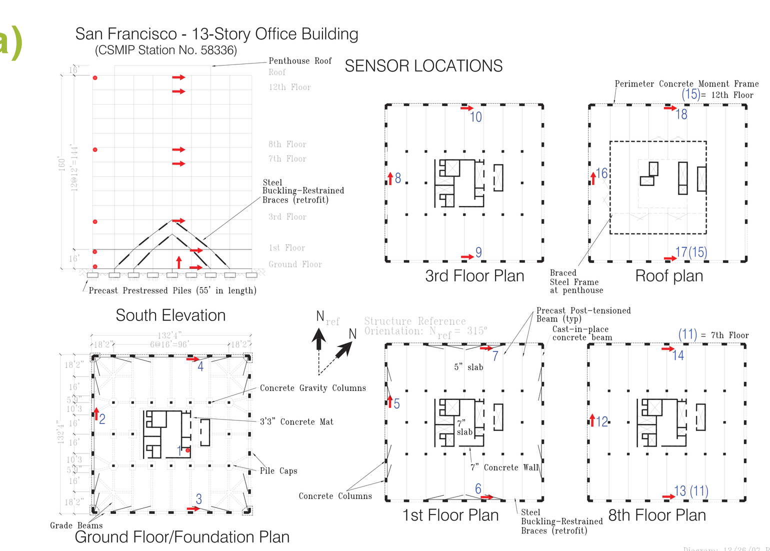


Figure 2: An equation for Inter-story Drift Ratio[5] and a sketch[6] of what the parameter describes.

(3a)



(3b)

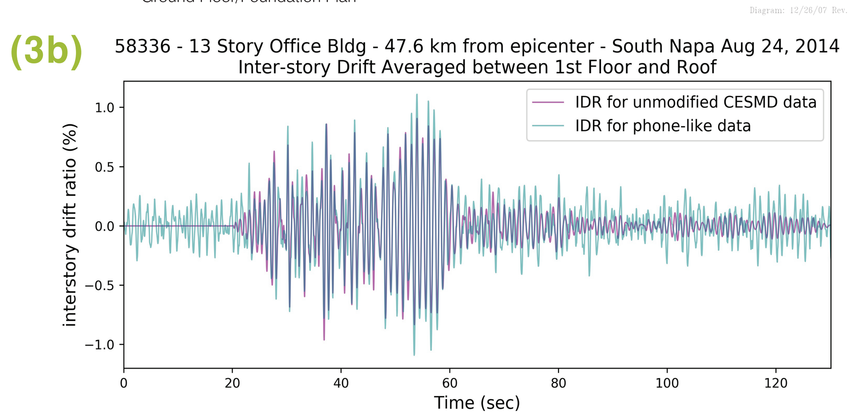


Figure 3a: Floor plans for a 13 story office building in San Francisco, CA with arrows to indicate the locations and orientations of CESMD accelerometers[3].
(3b) Inter-story drift ratios (averaged over the 1st-top floor) computed over time for the response of this building to the South Napa Earthquake in 2014. The teal represents data modified to mimic expected MyShake performance, and is compared to the violet record derived from the original high quality CESMD data.

Characterizing Expected Performance

We adapt data from the Center for Engineering Strong Motion Data (CESMD) repository[3] to quantify expected MyShake performance, and the thresholds above which we can reliably extract useful information.

The CESMD dataset spans buildings across the West Coast, and includes records from a variety of earthquakes over the course of a few decades. From this, we can explore the natural variability[8] in 'healthy' measurements within a single building that correspond to differences in signal to noise ratios, magnitude, epicentral distance, etc.

Table 1

58483 - 24 Story Residential Building - Reponse Values for Moderate-Sized Impulses

				North-South Component		East-West Component	
Event	Local Date	Magnitude (Mw)	Epicentral Distance (km)	Peak Acceleration (cm/sec^2)	Modal Frequency (Hz)	Peak Acceleration (cm/s^2)	Modal Frequency (Hz)
Lafayette	01 March 2007	4.2	18.1	25.715	1.928	20.144	2.38
Piedmont	20 July 2007	4.2	6.2	57.078	1.893	24.749	1.919
Alamo	05 September 2008	4.0	24.3	17.65	1.916	19.405	1.892
Berkeley	20 October 2011	4.0	7.3	72.733	2.206	55.37	2.382
Berkeley	20 October 2011 (night)	3.8	7.8	50.951	2.211	34.532	2.438
El Cerrito	05 March 2012	4.0	15	30.715	1.939	21.495	3.107
South Napa	24 August 2014	6.0	47	45.843	1.95	37.469	2.256
Berkeley	04 January 2018	4.4	6.3	59.949	1.932	56.713	2.273
				Average	**1.997**	*Average*	**2.331**
				STD	**0.132**	*STD*	**0.376**
				Unmodified CESMD data:		Unmodified CESMD data:	
				Average	2.023	*Average*	2.337
				STD	0.127	*STD*	0.107

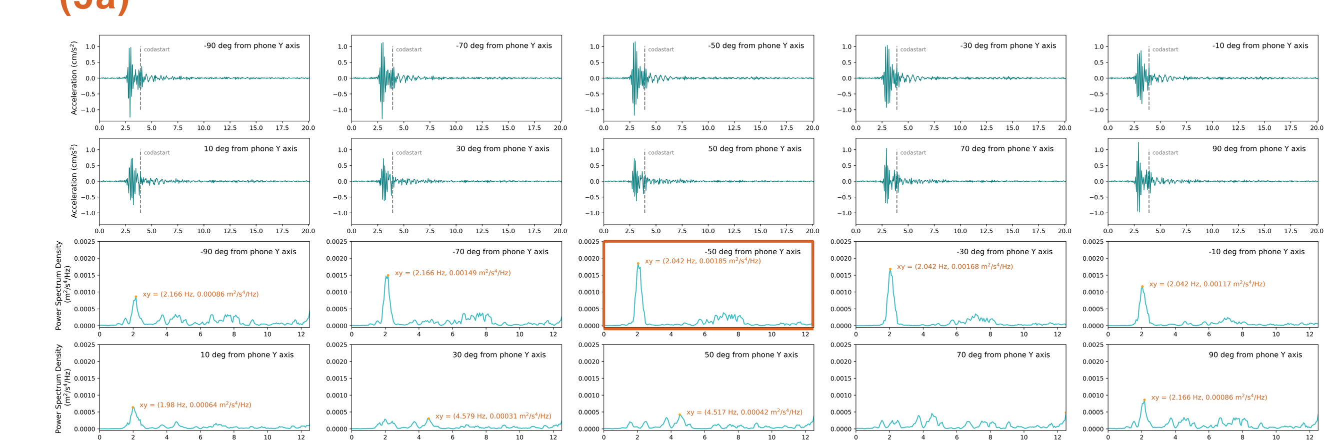
Table 1: A summary of how modal frequency, as measured by phone-like data from the roof of the 24 story building from Figure 4, varies with different excitations. The bottom portion compares the calculated MyShake values to those derived from the original high quality CESMD data[3].

Phones as Seismic Sensors

- **Sampling Rate:** MyShake utilizes the on board accelerometer in smartphones to record motion at a sampling rate of 25 Hz. We use a low sampling rate to accommodate the capabilities of the widest variety of accelerometer hardware on the market, as well as to manage power and memory demands.
- **Signal Quality:** 95% of the instrument 'background' noise across MyShake phones has been measured to be <0.0064 g, with a median of < 0.002 g. These values should fall as technology improves. For now, we require small local impulses to excite the fundamental frequency above the noise.
- **Orientation:** The three components of acceleration returned by MyShake phones is relative to the axes of the phone with no external reference frame. To orient our data in a consistent and useful way, we:

  1) Rotate the components until the ambient median Z approaches 1 g
  2) Systematically rotate the horizontalized XY components
  3) Transform these rotated signals into the frequency domain to seek the orientation which maximizes a single frequency peak and minimizes all others (demonstrated in figure below)

(5a)



Each axis of a building constitutes a degree of freedom characterized by a distinct modal frequency. In seeking to maximize a single frequency peak, we are orienting our data to align with the dominant axes of the buildings in which the phones are located.

(5b)

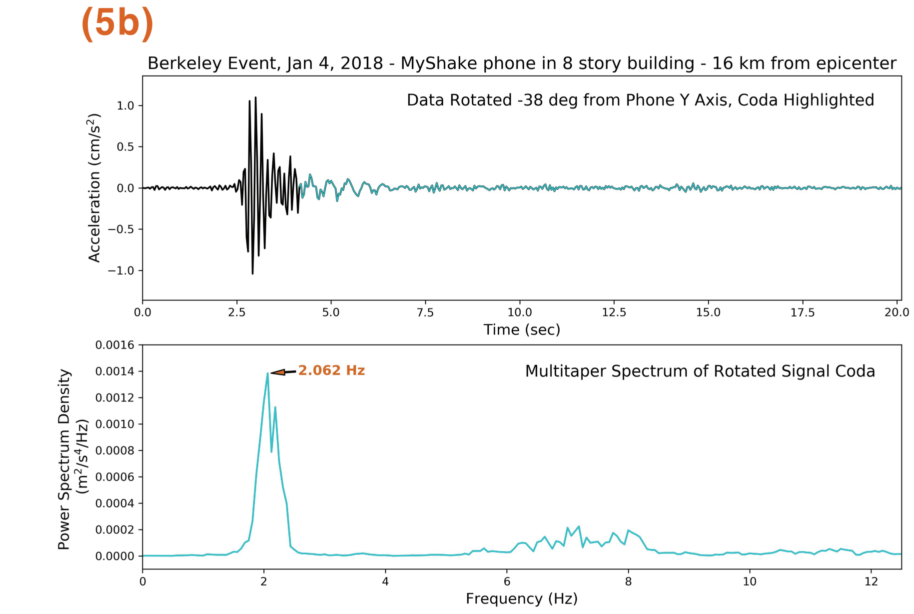


Figure 5 a & b: A validation of MyShake's ability to record a seismogram of high enough quality to extract a clear and believable modal frequency when a structure is agitated by a small local earthquake. **(a)** shows the effect of rotating the horizontal components to optimize a frequency peak while **(b)** highlights the rotation (-38 deg from Y) with the greatest peak. We determine the modal frequency of this 8 story building to be 2.1 Hz, which falls within the range of believable values for a building of this size[4]

Next Steps

- **Standardize and automate** the quality filtering and parameter extraction from MyShake data. This includes determining which factors, such as magnitude/distance ratio or signal-to-noise ratio, exert the strongest influence on a record's usability, and could be used as a discriminator.

- **Develop a database of buildings** frequented by MyShake users in order to establish 'healthy baselines' to which to compare the structural behavior recorded during a major, potentially damaging event.

- **Address the social considerations** that would accompany utilizing this data after a significant earthquake. What are the appropriate thresholds to flag buildings as potentially damaged? Who should be notified?

- **Develop a method of decoupling structural response from ground motion** information recorded by phones in order to use MyShake for the purposes of higher resolution intensity mapping and hazard estimation.

References

1) <https://www.shakealert.org/implementation/cisn/seismic-instrumentation/> Last accessed 5/9/2019
2) (~100 km² defined by the borders of the 12th Congressional District) <census.gov/mycd> Last accessed 5/9/2019
3) Center for Engineering Strong Motion Data <https://strongmotioncenter.org> Last accessed 12/8/2019
4) Arch 7210, Structural Design for Dynamic Loads, Lecture 6 (University of Virginia) http://web.arch.virginia.edu/struct/arch721/content/lectures/lec-05/ Last Accessed 12/8/2019
5) Alzughaibi, Ahmed A., et al. "Post-Disaster Structural Health Monitoring System Using Personal Mobile-Phones." 2019 IEEE Topical Conference on Wireless Sensors and Sensor Networks (WiSNet), 2019, pp. 1–4., doi:10.1109/wisnet.2019.8711805
6) Dai, F., Dong, S., Kamat, V.R., & Lu, M. (2011). Photogrammetry Assisted Measurement of Inter-story Drift for Rapid Post-disaster Building Damage Reconnaissance. Journal of Nondestructive Evaluation, 30, 201-212
7) Chopra, A.K. Dynamics of Structures, 5th ed. Pearsons, 2017
8) Clinton, J. F., Bradford, S. C., Heaton, T. H., & Favela, J. (2006). The observed wander of the natural frequencies in a structure. Bulletin of the Seismological Society of America, 96(1), 237-257.

For more information about MyShake as a seismic network, see:

Kong, Q., Patel, S., Inbal, A., & Allen, R. M. (2019). Assessing the sensitivity and accuracy of the MyShake smartphone seismic network to detect and characterize earthquakes. Seismological Research Letters, 90(5), 1937-1949.

Kong, Q., Allen, R. M., Kohler, M. D., Heaton, T. H., & Bunn, J. (2018). Structural health monitoring of buildings using smartphone sensors. Seismological Research Letters, 89(2A), 594-602.

Kong, Q., Allen, R. M., Schreier, L., & Kwon, Y. W. (2016). MyShake: A smartphone seismic network for earthquake early warning and beyond. Science advances, 2(2), e1501055.