

Ambient vibration analysis of high-rise buildings using MyShake smartphone data

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ABSTRACT

This study investigates the feasibility of using smartphones equipped with the MyShake application to measure the natural frequency and damping ratio of buildings from ambient vibrations. Originally developed as a citizen science tool, MyShake became widely adopted for delivering earthquake early warning (EEW) messages. It also autonomously records three-component acceleration data in 5-min segments to conserve battery. We developed an automated technique optimized for these recordings, using multi-taper spectral analysis and the half-power bandwidth method to extract dynamic building properties. To assess the influence of sensor noise, we simulated smartphone recordings by adding MyShake-equivalent noise to high-quality sensor data and confirmed that key frequency peaks remained detectable.

Field deployments across four buildings in the San Francisco Bay Area—ranging from mid-rise to tall structures—demonstrated that taller buildings consistently produced reliable measurements, even under low-wind conditions. In contrast, shorter buildings required stronger ambient excitations to yield accurate frequency estimates. Results from smartphone data closely aligned with those from previous studies using the traditional seismic sensors, validating the method's accuracy. By integrating ubiquitous smartphone sensing with operational modal analysis, this work presents a scalable, low-cost approach for continuous structural health monitoring, with strong potential for early detection of changes in high-rise buildings.

1. Introduction

Recent seismic events, such as the devastating 2023 M7.8 earthquake in Turkey, 2024 M7.4 earthquake in Taiwan, and the 1994 M6.7 Northridge earthquake, underscore the critical need for effective global structural health monitoring (SHM) system. These events highlight the inherent vulnerabilities in structural designs and the impacts of deterioration and modifications over time, which can compromise the integrity of buildings, bridges, and other infrastructure [1–3]. Studies have shown that the natural frequency and the damping ratio of the structures vary in response to strong wind events, in addition to the earthquake excitations [4,5].

In recent years, numerous studies have utilized modal analysis techniques based on ambient vibration recordings to identify structural properties and monitor changes over time, forming the core of classical SHM approaches. These methods often integrate ambient vibration data with numerical modeling to track variations in dynamic properties such as natural frequency and damping. For example, Bianconi et al. [6] and Standoli et al. [7] demonstrated how ambient vibration measurements can support the calibration of finite element models for assessing complex structures. Complementary efforts, such as those by Mohammed et al. [8], leveraged dense

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sensor arrays like the Community Seismic Network (CSN) [9] to measure building responses using low-cost MEMS accelerometers. Prieto and Kohler [10] applied coda wave interferometry to ambient recordings to detect time-varying changes in damping and velocity in high-rise buildings, even during nonlinear responses. Collectively, these studies highlight the growing potential of ambient vibration-based SHM techniques for scalable, non-intrusive monitoring. However, traditional SHM deployments remain resource-intensive, limiting their widespread implementation [11,12].

Several attempts have been made to leverage smartphone technology for SHM applications in buildings [13–16] and bridges [17, 18]. A comprehensive review by Sarmadi et al. [19] evaluated numerous research articles on smartphone sensing technology for SHM, highlighting the potential of smartphones as a cost-effective and versatile system for data collection in SHM applications. In experiments on a laboratory-scale suspended bridge, Zhao et al. [18] compared smartphone accelerometer data to conventional sensors for rapid damage assessment, finding good agreement between the two. These studies explored the accuracy and feasibility of using smartphones to quantify the dynamic behavior of structures by measuring the natural frequencies or displacements. Natural frequencies, which depend on a structure's physical properties such as mass, stiffness, strength, and damping, can indicate changes in the dynamic behavior of the structure when altered [20]. By monitoring these changes, it is possible to detect alterations in a structure's overall condition. Notably, natural frequencies decrease significantly during earthquake excitation but recover only if no permanent damage occurs [21], emphasizing the importance of ambient vibration measurements for setting the baseline [14,22].

Building on the advancements in smartphone-based sensing, the MyShake application [23] offers a promising solution for SHM by leveraging the widespread availability of smartphones. This free, globally accessible app not only provides earthquake early warning (EEW) messages as part of the USGS ShakeAlert system [24–26] but also autonomously collects three-component acceleration waveforms using onboard accelerometers. This capability enables the crowdsourced collection of earthquake data, an innovative approach that has engaged over 3.2 million users worldwide [27,28]. The greatest density of MyShake-enabled smartphones is currently in California where approximately 1 in 20 people have a phone with an active installation of MyShake.

The MyShake application strategically records only short durations of acceleration data to conserve the phone battery, necessitating separate analysis that considers these constraints. In addition to the length of the recording, the vibrations recorded by the MyShake phone have noise effects from environmental and cultural sources as well as hardware related sources. Despite this limitation, previous research has validated MyShake's effectiveness in capturing the natural frequencies of buildings during seismic events, a critical indicator for assessing structural health [12,23,29].

This research explores the feasibility of using smartphones equipped with the MyShake application to measure the natural frequency and damping ratio of buildings through ambient vibrations. We employ operational modal analysis (OMA) to examine the dynamic properties of buildings and provide a detailed methodological outline. Considering the implications of utilizing low-cost smartphone accelerometers and on-device data processing for SHM based on ambient vibrations, it is crucial to evaluate the viability of ambient recordings made with MyShake. Our approach involves initially simulating MyShake waveforms by integrating typical MyShake noise levels with data from traditional sensors. This simulation helps in understanding the noise characteristics and their impact on the data quality.

To validate the practical feasibility of employing MyShake ambient waveform recordings for OMA, we set up a controlled experiment and deployed several smartphones with the MyShake application installed in multiple buildings across the San Francisco Bay Area. Additionally, we developed and applied an automated technique specifically optimized for MyShake recorded data to measure the buildings' fundamental frequencies. This automated approach enhances the accuracy and efficiency of frequency measurements, making it a robust tool for large-scale SHM applications.

2. MyShake smartphone seismic network for structural health monitoring

The MyShake application, a free seismology tool available on smartphones, leverages onboard accelerometers to advance SHM. By autonomously recording acceleration waveforms during earthquakes, MyShake captures critical response data from the buildings in which the smartphones are located. However, continuous monitoring or streaming of data is impractical due to power and bandwidth constraints. Instead, the application uses a triggering mechanism to record data for short periods.

MyShake employs a 1-min ring buffer allowing recorded waveforms to start 1 min before the trigger and continue for an additional 4 min, capturing a total of 5 min of three-component acceleration data. These recordings are then uploaded to a central server for archival and subsequent analysis. The application utilizes two strategies for data collection: an auto-collection strategy via a local artificial neural network (ANN) model within the app, and remote triggering through the EEW server. The ANN model is designed to differentiate between earthquake-like ground motions and everyday movements, while the EEW server automatically triggers recording during seismic events on the phones at rest.

3. Automated building natural frequency measurement technique

The identification of natural frequencies and damping ratios are performed in both the frequency domain (using methods such as the transfer function method and the power spectral density (PSD) method) and the time domain (using methods such as the multiple-input multiple-output (MIMO) system identification method and the random decrement method) [30,31]. We developed an automated natural frequency measurement technique based on the PSD method, specifically designed for the real-time assessment of building dynamics using the MyShake 5-min acceleration recordings. This technique employs Multi-taper Spectral Analysis [32–34] to extract power spectra from waveform data, selecting the relevant frequency band based on an empirical formula from the American Society of Civil Engineers (ASCE) 7–22 standards [35].

$$T = C_t h^x$$

Where T is the approximate building period in seconds, h is the height of the building in feet, and C_t and x are the coefficients and exponent, respectively that depends on the structural design system. We refer the readers to Patel et al., [12] for details.

By automating the process of natural frequency identification, this method addresses the challenges and limitations inherent in manual frequency measurements, which are labor-intensive and prone to errors and inconsistencies. Notably, the automation facilitates the efficient, scalable assessment of multiple structures, essential for scaling structural health monitoring in urban environments or in response to natural disasters.

The effectiveness of this technique hinges on its ability to adapt to the unique dynamic characteristics of different buildings, which vary based on factors such as height, construction material, and structural design. The algorithm optimizes the number of time windows and their duration, using a peak detection algorithm to focus on significant power peaks that stand out from the background noise, ensuring accurate and reliable measurements as well as optimized frequency resolution. Frequency resolution, calculated as the inverse of the time window length, determines the ability to distinguish between closely spaced frequency components, with longer windows providing higher resolution. For taller buildings, longer time windows are used to enhance frequency resolution and reduce spectral leakage, taking advantage of their lower natural frequencies and greater signal stationarity (Fig. 1). A longer window provides a more detailed view of the frequency spectrum by reducing the width of the main lobe in the spectral leakage, thus minimizing interference from side lobes [32]. Conversely, shorter buildings with generally stiffer structures benefit from shorter time windows that accurately capture their more rapid dynamic responses, avoiding the dilution of significant frequency information.

We implemented the half-power bandwidth method [36,37] for measuring the damping ratio of the buildings using the MyShake acceleration data. This method involves analyzing the PSD curve, which represents the steady-state amplitude of accelerations at a specific point in the structure when subjected to a harmonic load applied at another point. By examining this curve at its natural frequencies, the damping characteristics can be determined experimentally. The key aspect of the half-power bandwidth method is identifying the frequencies at which the amplitude drops to $1/\sqrt{2}$ (approximately 70.7 %) of its peak value. These frequencies are referred to as the half-power points. The damping ratio, ζ , is then calculated using the relationship $\zeta = \Delta\omega/2\omega_n$, where $\Delta\omega$ is the difference in frequencies between the half-power points, and ω_n is the natural frequency of the system. We chose this method for its simplicity and effectiveness in providing an accurate estimation of damping in structural systems.

This methodology not only improves the precision and efficiency of natural frequency measurements but also integrates seamlessly into existing SHM frameworks, providing a robust tool for engineers and researchers. The adaptability of the technique to various building types and its capacity for handling large datasets can make it an invaluable asset in the ongoing development of predictive maintenance strategies and safety evaluations in civil engineering. The next steps in this research will focus on refining the empirical formulas used for frequency band selection and enhancing the algorithm's ability to distinguish between noise and structural responses, further improving the accuracy of fundamental frequency and damping ratio determinations.

4. Validating automated measurements with traditional sensors

The use of smartphone accelerometers for SHM offers innovative possibilities but also presents inherent challenges. One significant challenge is the intrinsic noise levels in smartphone accelerometers, which can mask the signals that indicate a structure's natural frequencies—signals essential for evaluating its structural health [23,38,39]. To address this limited fidelity, our experimental design requires minimal input motions, such as a significant wind event, to excite the natural frequencies to measurable levels. This approach effectively distinguishes between sensor noise and building ambient vibrations that are sensitive enough to the building structure to

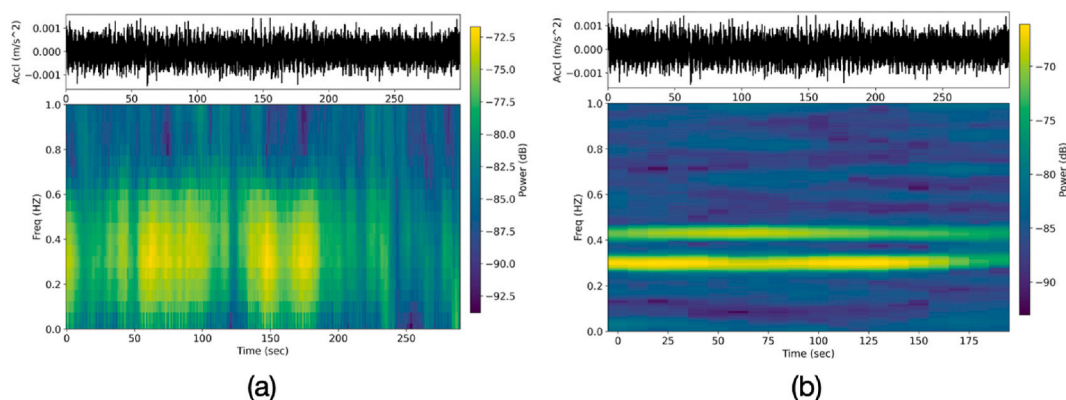


Fig. 1. Effect of time window length on frequency resolution for buildings with low fundamental frequencies. (a) Power spectral density (PSD) computed using a 10-s time window. (b) PSD computed using a 100-s time window. Longer time windows provide higher frequency resolution by narrowing the spectral peaks, which helps in distinguishing closely spaced frequency components and reduces spectral leakage. This is particularly important for tall buildings with low natural frequencies, where increased resolution improves the reliability of peak identification.

yield reliable measurements. For context, measurements of modal frequencies under seismic loading are detailed in Patel et al., [12].

To assess the viability of smartphones in measuring building frequencies, we initiated validation using ambient vibrations recorded by a traditional sensor. We recorded three days of ambient vibration in a 197-m-tall building (Building 1, Millennium Tower) in windy conditions using an EpiSensor force-balance accelerometer produced by Kinemetrics Inc. To emulate smartphone-based measurements, we trimmed a 5-min segment from the EpiSensor recording and added noise representative of MyShake smartphones, derived from historical recordings (Fig. S1). We also downsampled the EpiSensor waveform segment to 50 Hz to match the sampling frequency of the MyShake recording [12]. The automated natural frequency analysis technique described earlier was then applied to both the original EpiSensor recording and the noise-augmented version.

Despite noticeable differences in the time-domain signals due to added noise, the PSD analysis revealed three prominent and consistent frequency peaks in both cases (Fig. 2), demonstrating the robustness of our frequency extraction method even under degraded signal conditions. The added noise replicates typical MyShake accelerometer behavior, characterized by an average noise floor of approximately -75 dB. Notably, smartphone noise exhibits greater variability at low frequencies (ranging from -50 to -80 dB) and more stable, lower levels at higher frequencies (around -78 to -85 dB). During our building deployments, we observed PSD noise levels near -70 dB, with structural signals often exceeding -60 dB, enabling reliable detection of natural frequencies. For a detailed characterization of the MyShake sensor performance and noise spectra, we refer readers to Patel et al. [12].

5. Deployment and analysis of MyShake ambient vibrations for structural health monitoring

5.1. Field deployment strategies for MyShake smartphones

To assess the feasibility of utilizing MyShake smartphones for SHM, a field study was conducted across multiple buildings in the San Francisco Bay Area. The objective was to capture vibrational data from various building structures, enabling a detailed analysis of their natural frequencies (see Table 1). The study encompassed a diverse range of building designs, differing in structural composition and height. The structures in the study included the 197-m Millennium Tower at 301 Mission St and the 138-m high-rise at 188 Minna St in San Francisco, both reinforced concrete frame buildings. The Pacific Park Plaza in Emeryville, a 95-m ductile moment-resistant reinforced concrete-framed structure, and a 54-m lift-slab building at 2150 Shattuck Ave in Berkeley, were also included (Fig. 3).

Smartphones such as the Google Pixel, Samsung Galaxy, and Motorola Razr were arbitrarily positioned on various floors within each building to capture a comprehensive range of vibrational data. In some cases, the devices were securely taped to the floor to minimize extraneous movements and ensure data accuracy. To evaluate the impact of phone stability on data quality, additional smartphones were placed adjacent to the secured ones but left untaped. This setup facilitated an assessment of data reliability and consistency across different elevations and deployment methods within the buildings. The phones were oriented along the building's principal axes [40] to capture the dominant vibrational modes.

Table 1 summarizes the deployment details and results. For each building and phone, we report the floor location, attachment method (taped or untaped), and the measured **fundamental frequencies** (denoted as f_{0X} , f_{0Y} for the two horizontal axes), as well as the associated damping ratios (ζ_{0X} , ζ_{0Y}) estimated using the half-power bandwidth method. These measurements offer insights into the dynamic behavior of the buildings and the consistency of results across phone models, placements, and floors.

Data collection occurred under varying wind conditions, with wind speed data sourced from the nearest National Weather Service (NWS) station, PXOC1, located at the San Francisco Pier 1 [41]. The NWS measures wind speed by averaging observed values over a 2-min period, defining wind gusts as sudden, brief increases in speed. Gusts are reported when the peak wind speed reaches at least 8.23 m/s (16 knots) and the variation between peaks and lulls is at least 5.14 m/s (10 knots) [42]. Forecasted wind data were retrieved

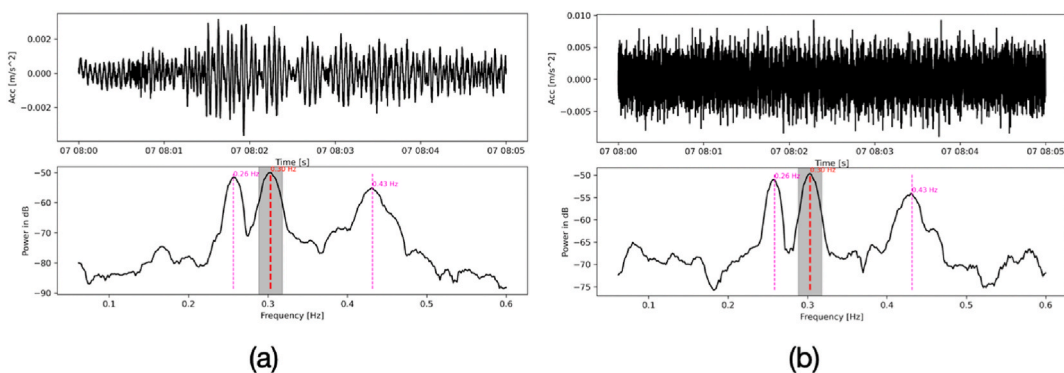


Fig. 2. Validation of the automated PSD-based frequency measurement technique using traditional sensor data and simulated MyShake noise of length 5 min. (a) Power spectral density (PSD) computed from a 5-min ambient vibration recording using an EpiSensor accelerometer in Building 1 (Millennium Tower, 197 m). (b) Same recording with added MyShake-equivalent noise. Both spectra reveal three prominent peaks at 0.26 Hz, 0.30 Hz, and 0.43 Hz, corresponding to the building's modal frequencies. The red and magenta dashed lines indicate detected peaks, with red marking stronger (higher signal-to-noise ratio) components. The shaded gray region around the red peak illustrates the frequency resolution. Despite added noise, the automated method reliably identifies the same dominant frequencies, demonstrating robustness to smartphone sensor limitations.

Table 1

MyShake Smartphone placement in different residential buildings and its corresponding natural frequency measurements. The height and material information are obtained from the OpenStreetMap (<https://www.openstreetmap.org/>), Google Earth (<https://earth.google.com/web>) and OSM buildings (<https://osmbuildings.org/>) database.

Building/ Phone Codename	Location	Height (in m)	Material	Smartphone Model	Total Floors	Sensor Floor	Remarks	f_{0x}, f_{0y} (Hz)	ζ_{0x}, ζ_{0y}
Building 1/ Phone a	301 Mission St, San Francisco (Millennium Tower)	197	Reinforced Concrete Frame	Google Pixel 8	58	56	Untaped	0.3 ± 0.00 0.26 ± 0.00	0.07 ± 0.001 0.07 ± 0.001
Building 1/ Phone b	301 Mission St, San Francisco (Millennium Tower)	197	Reinforced Concrete Frame	Motorola Razr	58	34	Taped	0.3 ± 0.02 0.26 ± 0.012	0.07 ± 0.005 0.07 ± 0.003
Building 1/ Phone c	301 Mission St, San Francisco (Millennium Tower)	197	Reinforced Concrete Frame	Samsung Galaxy S8	58	34	Untaped	0.32 ± 0.08 0.26 ± 0.05	0.07 ± 0.012 0.08 ± 0.001
Building 2/ Phone a	188 Minna St, San Francisco	138	Reinforced Concrete Frame	Samsung Galaxy S23	42	27	Taped	0.33 ± 0.12 0.40 ± 0.13	0.09 ± 0.027 0.07 ± 0.029
Building 3/ Phone a	6363 Christie Ave, Emeryville (Pacific Park Plaza)	95	Reinforced Concrete Frame	Google Pixel 6a	30	15	Taped	0.47 ± 0.03 0.46 ± 0.04	0.059 ± 0.02 0.065 ± 0.04
Building 3/ Phone b	6363 Christie Ave, Emeryville (Pacific Park Plaza)	95	Reinforced Concrete Frame	Google Pixel 6	30	16	Taped	0.48 ± 0.06 0.48 ± 0.6	0.085 ± 0.05 0.081 ± 0.05
Building 4/ Phone b	2150 Shattuck Ave., Berkeley (SkyDeck)	54	Lift Slab	Google Pixel 1	14	13	Untaped	N/A, 0.87 ± 0.11	N/A 0.08 ± 0.03
Building 4/ Phone c	2150 Shattuck Ave., Berkeley (SkyDeck)	54	Lift Slab	Google Pixel 7	14	13	Taped	0.82 ± 0.20 0.80 ± 0.22	0.09 ± 0.08 , 0.12 ± 0.04
Building 4/ Phone d	2150 Shattuck Ave., Berkeley (SkyDeck)	54	Lift Slab	Google Pixel 6a	14	13	Untaped	0.85 ± 0.18 , 0.7 ± 0.17	0.07 ± 0.02 , 0.10 ± 0.08

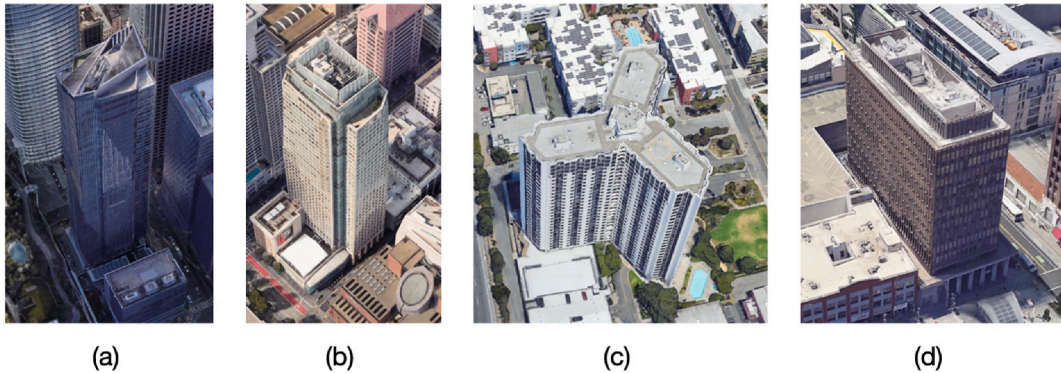


Fig. 3. Satellite images of the buildings used in the study, showcasing the diversity in structural composition and height. The buildings included in the study are: (a) Building 1, located at 301 Mission St, San Francisco (Millennium Tower), a 197-m tall high-rise with a reinforced concrete frame; (b) Building 2, situated at 188 Minna St, San Francisco, a 138-m tall structure also featuring a reinforced concrete frame; (c) Building 3, at 6363 Christie Ave, Emeryville (Pacific Park Plaza), a 95-m tall building with a reinforced concrete frame; and (d) Building 4, located at 2150 Shattuck Ave., Berkeley (SkyDeck), a 54-m tall building constructed using the lift slab method. These images illustrate the different building types and heights analyzed in the study to assess the effectiveness of MyShake-enabled smartphones in capturing vibrational data. Image source: Google Earth.

from NWS webpage every 6 h, and the MyShake phones were triggered whenever wind speeds exceeded a predefined threshold, allowing a detailed analysis of wind-induced vibrations on the buildings' fundamental frequencies.

Over six months, waveform data was collected to ensure a robust dataset reflecting varying environmental conditions. The MyShake phones were triggered remotely at selected times daily and whenever regional wind speeds exceeded 12 m/s. Each trigger typically resulted in a 5-min waveform, with data transmitted to the server a few hours later.

5.2. Natural frequency measurements using MyShake smartphones

MyShake smartphones, when placed at rest in buildings, can record seismic acceleration data, which can then be used to determine the dynamic characteristics of the buildings, such as natural frequencies and damping. It is important to measure vibrations in multiple directions, particularly the two orthogonal horizontal components, to get a comprehensive understanding of a structure's dynamic behavior. This is especially relevant for complex structures like tall buildings. Fig. 4 presents the natural frequency measurements performed for the acceleration recording on the 56th floor of 301 Mission St, San Francisco (Building 1; Millennium Tower) on two windy days. Each subfigure's top panel shows the unfiltered 5 min of acceleration recordings from the MyShake phones, while the bottom panel displays the natural frequency measurements using the automated technique described above. The red line indicates the automated natural frequency measurement, and the width of the gray region represents the frequency resolution.

The smartphones were deployed in alignment with the building wall orientation. The measured fundamental frequencies on the two horizontal components differ, with the X component at 0.30 Hz and the Y component at 0.26 Hz. These fundamental frequency measurements are consistent over time and across different floors, as evidenced by the measurements taken from a phone deployed on the 34th floor (Fig. S3). The measured natural frequencies using MyShake smartphones agree with the measurements using the traditional sensor in the same building (Fig. 2). It is interesting to observe that the higher building harmonics also get excited for several recordings as is picked as the secondary peaks.

Fig. 5 illustrates the natural frequency measurements for Building 3 using the same approach, performed on a MyShake smartphone recording on the 15th floor. The natural frequency for both horizontal components is measured to be 0.47 Hz. Fig. 5a, b, and 5c each show a single peak frequency measurement obtained using the PSD method. In contrast, Fig. 5d displays two peaks: the dominant peak, marked by a red dashed line, and a secondary peak, marked by a magenta dashed line. The dominant and the secondary peaks are picked based on its relative power and the signal-to-noise ratio. The signal-to-noise ratio is defined as the ratio of the power of the natural frequency peak (signal) to the power of the background noise, calculated within the PSD domain.

The MyShake smartphones for the Building 1 (Millennium Tower) were also triggered during low-wind days to collect the acceleration data. It is noteworthy that natural frequency measurements are feasible on less windy days for tall buildings such as this, where measurements were conducted on the 34th and 56th floors. At these elevations, the exposure to wind-related vibrations is greater, even on calmer days, enhancing the signal strength. Observations indicate that frequency measurements on less windy days

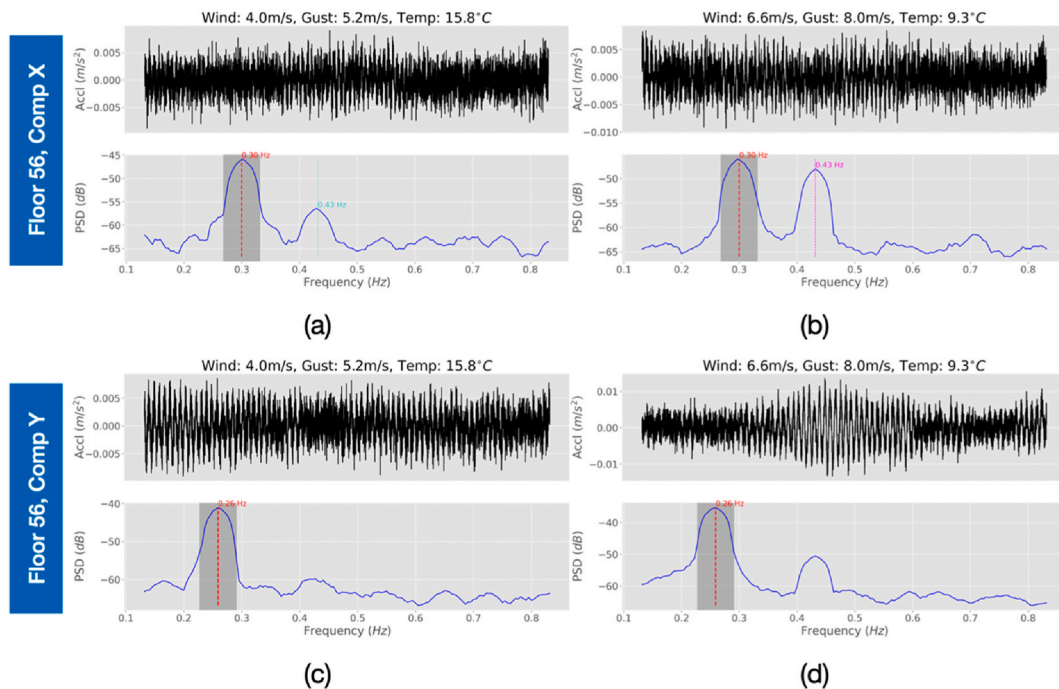


Fig. 4. Natural frequency measurements for a phone deployed on the 56th floor of 301 Mission St, San Francisco (Building 1, phone a; Millennium Tower) for two different windy days. (a, c) 2024-01-31 17:16:14 UTC and (b, d) 2024-02-04 15:48:48 UTC. The total number of floors in the building is 58. The two rows show the measurements for the two orthogonal horizontal axes. The top panel in each subfigure shows the unfiltered acceleration recording on the MyShake phones and the bottom panel shows the natural frequency measurement using the automated measurement technique. Notice that the fundamental frequency measured on the X component (top panel) is 0.30 Hz and on the Y component (bottom panel) is 0.26 Hz. These frequencies are consistent with the slightly different natural frequencies of the two orthogonal axes of the building. The natural frequencies are measured using the automated PSD method where the dominant peak is indicated by the red dash line with the gray shaded region representing the frequency resolution. The magenta and cyan dashed lines represent the secondary and tertiary peaks based on its relative power and signal to noise ratio.

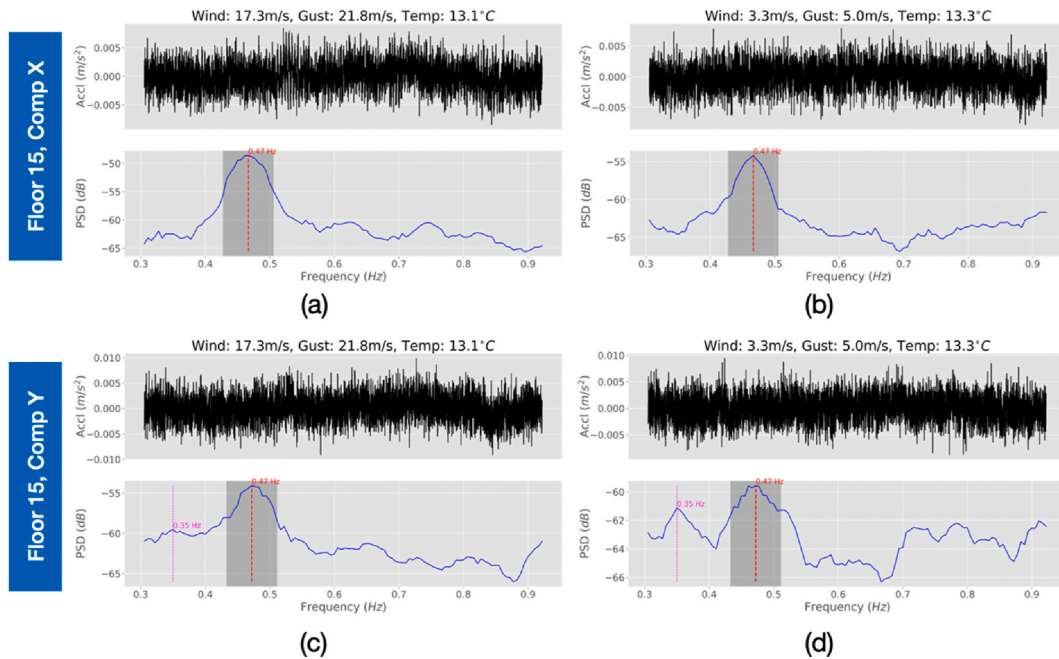


Fig. 5. Natural frequency measurements for a phone deployed on the 15th floor of 6363 Christie Ave, Emeryville (Building 3, phone a; Pacific Park Plaza) for two different days. (a, c) 2024-02-05 03:33:26 UTC and (b, d) 2024-02-19 19:26:54 UTC. The total number of floors in the building is 30. The two rows show the measurements for the two orthogonal horizontal axes. The top panel in each subfigures shows the unfiltered acceleration recording on the MyShake phones and the bottom panel shows the natural frequency measurement using the automated measurement technique. Notice that the fundamental frequency measured on the X component (top panel) is 0.47 Hz and on the Y component (bottom panel) is also 0.47 Hz.

are consistent with those recorded on windy days for both orthogonal components (See Figs. 4 and 6). The ability to detect natural frequencies during relatively calm days suggests that the data can be reliably used for continuous SHM of taller buildings, regardless of wind speeds.

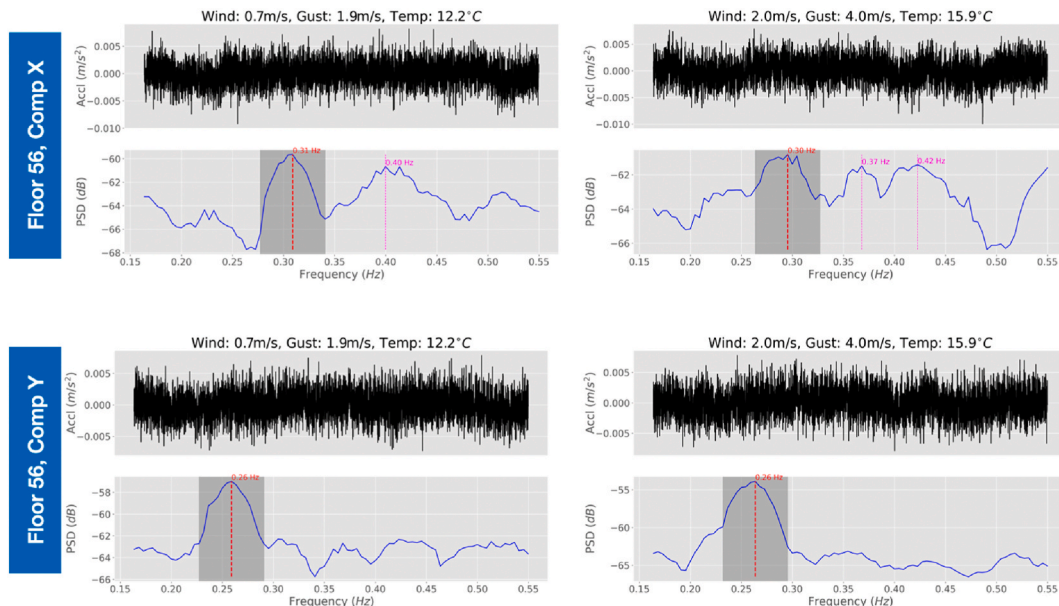


Fig. 6. Natural frequency measurements for a phone deployed on the 56th floor of 301 Mission St, San Francisco (Building 1a; Millennium Tower) for two different low-wind speed days. The two rows show the measurements for the two orthogonal horizontal axes. The top panel in each subfigures shows the unfiltered acceleration recording on the MyShake phones and the bottom panel shows the natural frequency measurement using the automated measurement technique.

However, the scenario differs for shorter buildings, where many measurements are automatically rejected due to lower signal strength, often drowned out by the noise levels. Typically, shorter buildings in urban settings are less influenced by wind induced ambient vibrations, which rarely reach the necessary intensity to robustly excite structural frequencies. Nonetheless, under sufficient wind exposure and wind strength, even shorter buildings can reliably yield measurements of natural frequencies (Fig. S5).

5.3. Longitudinal analysis of the natural frequency measurements

In our study, the primary goal is to understand the feasibility of modal frequency tracking over time to monitor the long-term stability and health of buildings. By analyzing the variations in these frequencies, we aim to identify any trends that may indicate shifts in structural integrity, potential damage, or changes in material properties due to environmental influences or aging. Specifically, we expect to see patterns that could signal either gradual deterioration or improvements following retrofitting efforts.

Over a six-month period, we utilized MyShake-enabled smartphones in four distinct buildings to undertake systematic recordings. This methodical approach was crucial to establish a comprehensive baseline of each building's response to varying environmental conditions, including fluctuations throughout the day and under different wind intensities. Regular monitoring of fundamental frequencies and their variations allowed us to assess the impact of some environmental factors, such as wind and temperature, on the dynamic responses of the buildings. The importance of the regular recordings cannot be overstated, as they provide necessary accuracy in our analyses amid the significant variability and uncertainties associated with environmental factors. This rigorous approach is key to capturing a detailed and accurate understanding of how the buildings react under varied environmental scenarios.

To achieve this, we applied a weighted trend analysis to the fundamental frequency measurements collected from the buildings. This analysis prioritized data based on the frequency resolution and the signal-to-noise ratio (SNR) of the measured frequencies, emphasizing higher quality measurements and diminishing the impact of less reliable data points. The reliability of each measurement was quantified by comparing the SNR of the Power Spectral Density (PSD) peak of the fundamental frequency against the background PSD level. Outliers in the data were identified and removed using statistical methods based on the variance of the measurements. This process ensured that the final dataset used for trend analysis was robust and reliable, minimizing the impact of anomalies caused by transient events or measurement errors.

Fig. 7 illustrates the fundamental frequency and damping ratio measurements for Building 1 (Millennium Tower) over several months, specifically for phone “a” located on the 56th floor. The top panel of Fig. 7 (a & b) shows that measurements with higher SNR—indicated by larger, darker circles—are more consistent with the modal frequency values and exhibit less variability. Notably, the measurements of the two horizontal components, aligned along the principal axes of the building, differ—a characteristic feature of this building—and these differences in natural frequency between the two components remained consistent over the six-month period of the study.

Several studies suggested that the variations in environmental conditions (such as wind, temperature, humidity) and operational conditions (such as occupancy levels, heavy machinery inside the building, adjacent construction etc.) can influence the measured structural response of buildings [43,44]. Surprisingly, we see little evidence of a consistent relationship between wind speeds and temperature with the signal strength of the natural frequency excitation during the course of our analysis. There are specific instances, such as around 2024-02-01, 2024-02-18, and 2024-05-20 in Fig. 7a, that demonstrate that SNR for natural frequency measurements depends on increased wind or gust speeds. A higher SNR on 2024-03-15 coincides with increased temperatures. Similar trends are observable for the Y component in Fig. 7b.

In addition to fundamental frequency measurements, Fig. 7 also examines the damping ratio of Building 1, a 197-m-tall structure,

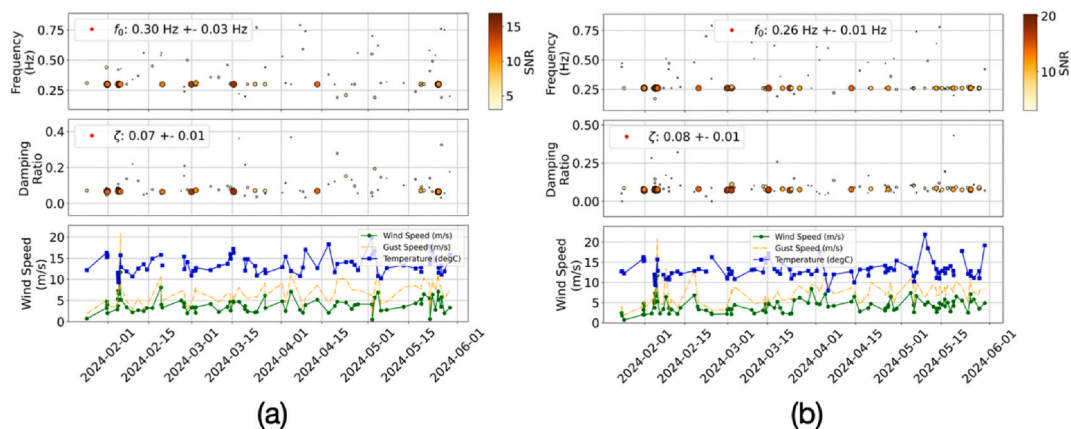


Fig. 7. Natural frequency and damping ratio measurements over several months for Building 1, phone a (56th floor, Millennium Tower, San Francisco) for (a) the X component and (b) the Y component. The top panel shows the natural frequency measurements, and the middle panel shows the damping ratio measurements using the half-power bandwidth method. The color intensity and the size of the points corresponds to the SNR, highlighting the reliability of each measurement. The bottom panel shows the variations of the wind speed (green line), gust speed (orange line) and temperature (blue line) for each fundamental frequency measurement.

across several months. The damping ratio, which is critical for understanding how energy is dissipated within the structure during oscillations, is depicted in the middle panel of Fig. 7 using the half-power bandwidth method. For Building 1, the measured mean damping ratios were found to be exceptionally low, with 0.7 % for the X component and 0.8 % for the Y component. These values are significantly lower than the typical damping ratios expected for a building of height 197 m, which generally range from 1 % to 3 % in seismic vibration conditions [45]. However, the damping ratios for tall buildings can be as low as 0.6 % under ambient vibration conditions, particularly when dealing with low-amplitude oscillations [37,46]. The lower damping ratios observed could indicate a higher stiffness in the building's structure or possibly reduced energy dissipation capabilities, which could have implications for the building's response to dynamic loading such as wind and seismic activities. Further investigation into these lower-than-expected damping values could provide critical insights into the structural health of the building, potentially highlighting areas for focused structural analysis and maintenance.

The relationship between the measurements in the two horizontal components (X and Y) for the Building 1 (Millennium Tower), phone "a" was also inspected to understand the environmental and operational effects on modal parameters (see Fig. 8). The plot shows the SNR values of the fundamental frequency measurements for both components along the two axes. We observe a clustering of data points with low SNR values, particularly around 3 to 5 for both X and Y components, indicating a concentration of less reliable measurements. However, as the SNR increases, there is a noticeable dispersion, with some measurements showing significantly higher SNR values for the Y component compared to the X component. This dispersion indicates variability in measurement reliability across the two components. The observed differences in SNR, coupled with directional dependence, suggest that the building responds more strongly to external forces in one direction, potentially due to the exposure to wind in one direction more than other, structural characteristics or the distribution of mass and stiffness.

6. Cross-correlating MyShake recorded waveforms in buildings

To ensure the reliability of measurements essential for structural health monitoring, we employed cross-correlation and cross-spectral density analyses between selected MyShake recorded waveforms as an alternative method to the traditional PSD analysis. These techniques are crucial as they quantify the consistency and reliability of the recorded data, helping to identify shared frequency components and measure signal coherence. High correlations between waveforms indicate reliable data, crucial for accurate interpretations of a structure's health. For instance, by comparing recordings from different times or floors within the same building, we can attribute the measured frequency responses to the structural effects instead of the local non-structural effects in time or space. Such comparisons are pivotal for validating the data selection and the subsequent analytical processes.

Fig. 9 illustrates the cross-correlation and cross-spectral density of two MyShake waveforms recorded simultaneously on the 56th floor and 34th floor of the same building (2024-02-05 03:33:25 PT). The PSD method-based signal-to-noise ratio of the natural frequency measurements for the two records were significantly high (18.7 measured at the 56th floor and 14.6 at the 34th floor). The two waveforms were cross correlated after bandpass filtering around the expected fundamental frequency obtained from ASCE 7-22 standards. The peak frequencies observed in the cross-spectral density plot match the natural frequencies determined by the PSD method, including the first harmonic, confirming the measurements' reliability. This finding underscores the effectiveness of the MyShake device in capturing relevant structural data and serves as a cross-validation of the PSD method's results.

Additionally, we analyzed ambient vibration data recorded at different times using the same MyShake device (at 56th floor of the

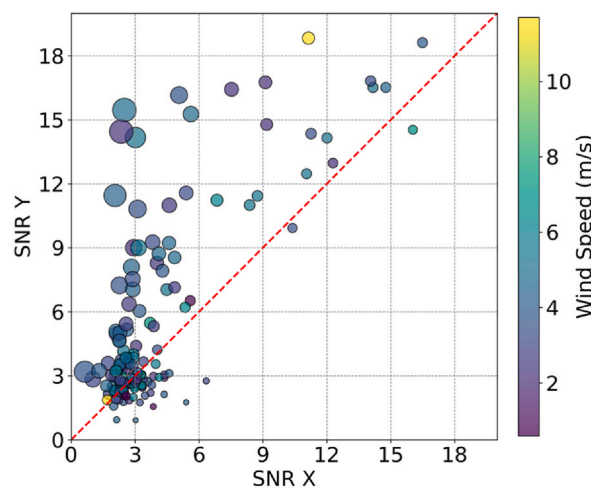


Fig. 8. Comparison of signal-to-noise ratio (SNR) for natural frequency measurements along orthogonal directions in Building 1 (Millennium Tower, phone a). Each data point represents a measurement of the fundamental frequency using MyShake recordings from the 56th floor. The x-axis and y-axis correspond to the SNR of the X and Y horizontal components, respectively. The color scale indicates wind speed at the time of measurement, and the size of the data points reflects the ratio of SNR between the Y and X components. The red dashed line denotes the 1:1 ratio. While most measurements cluster around moderate SNR values, several show directional variability.

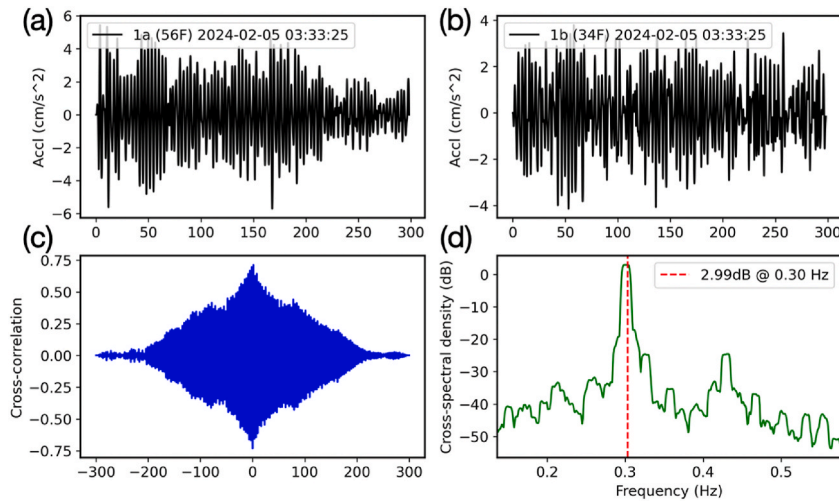


Fig. 9. Cross-correlation and cross-spectral density of two MyShake waveforms recorded in the same building at the same time (2024-02-05 03:33:25 PT) for component X. (a) MyShake waveform recorded at the 56th floor of Building 1 (Millennium Tower, San Francisco). (b) MyShake waveform recorded at the 34th floor of Building 1 (Millennium Tower, San Francisco). (c) Cross-correlation of the two waveforms (d) Cross-spectral density of the two waveforms. Notice that the peak frequency in the cross-spectral density plot is the fundamental frequency of the building.

Building 1) to understand how the structural responses vary over time. Although the correlation was not as strong as in the simultaneous recordings, reliable measurement of the building's natural frequencies was still possible, as shown in Fig. 10. This analysis helps identify consistent vibration patterns or frequencies inherent to the structure, indicative of its natural frequencies.

7. Discussion

The remote MyShake measurements, utilizing smartphones deployed in multiple buildings of varying heights, corroborate the established dynamic theory that taller buildings typically exhibit lower fundamental frequencies [47,48]. This observation is attributed to the increased mass and height, which inherently decreases the stiffness and thereby lowers the natural frequencies ($f \propto \sqrt{k/m}$, where k is stiffness and m is mass). Taller buildings, therefore, exhibit larger amplitude responses to ambient vibrations, enhancing their detectability via MyShake's application. This remote smartphone-based detection is particularly advantageous for tall buildings, as their lower frequencies can be identified even in low-wind conditions. In contrast, shorter, stiffer buildings possess higher natural frequencies, resulting from their greater relative stiffness and smaller mass. The amplitude of vibrations at these frequencies is typically lower under ambient conditions, necessitating more substantial excitations—such as those from strong winds or seismic

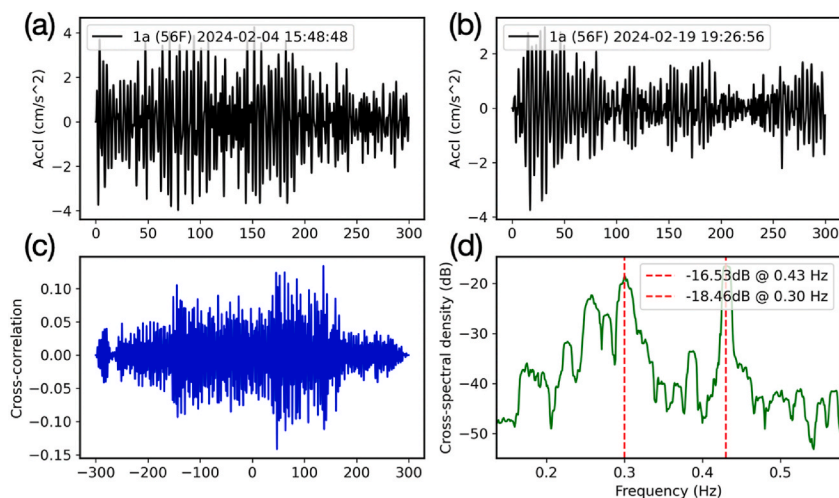


Fig. 10. Cross-correlation and cross-spectral density of two MyShake waveforms recorded in the same building at different times for component X. (a, b) MyShake waveform recorded at the 56th floor of Building 1 (Millennium Tower, San Francisco) at times 2024-02-04 15:48:48 and 2024-02-19 19:26:56 (c) Cross-correlation of the two waveforms (d) Cross-spectral density of the two waveforms.

events—to generate reliable measurements. The smartphone's ability to capture these subtler high-frequency signals is crucial, yet often challenging without significant external influences to amplify the building's motion. Nevertheless, reliable measurements of natural frequency in shorter buildings can be achieved by conducting repeated MyShake measurements, effectively capturing the significant excitation of natural frequency.

We observed slight variations in the fundamental natural frequencies of buildings along two orthogonal axes. The natural frequency of a building can differ along its principal axes due to various factors such as geometry, mass distribution, stiffness properties, and construction materials. For instance, Building 1 (Millennium Tower) has different fundamental frequencies along its principal axes (0.3 Hz along one axis and 0.26 Hz along the other). This variation is likely influenced by its complex construction and foundation system, highlighting the importance of considering axis-specific behavior when evaluating a building's dynamic performance.

The natural frequency measurements for Building 1 (Millennium Tower) derived from the MyShake data align with its estimated fundamental frequency from the ASCE 7–22 standards and the expected modal shape behavior for a building of this height. The MyShake measurements for the 34th and 56th floors of the 56-floor building showed that the amplitude of the PSD peak for the fundamental frequency measurement at the 56th floor was higher than that at the 34th floor, which is consistent with the dynamic characteristics of a tall, cantilevered structure (See Fig. 6 in SI). Furthermore, the natural frequency measurements based on MyShake waveform recordings are consistent with those obtained from the EpiSensor force-balance accelerometer produced by Kinemetrics Inc measured on the 34th floor (Figs. 2 and 4). The natural frequencies measured using EpiSensor are 0.26 Hz, 0.30 Hz, and 0.43 Hz. Since the EpiSensor was not deployed along the building's principal axes, each recording component captured all three dominant frequencies. However, the MyShake phones were deployed following the building's wall orientation, allowing for a clear distinction between the natural frequencies measured along the two axes. The frequency measurement of 0.43 Hz is likely the first harmonic of the building, observed reliably in both traditional sensor and some MyShake smartphone measurements.

Building 3 (Pacific Park Plaza) in Emeryville has been extensively instrumented by the USGS meaning that its natural frequencies have been measured using various methods over the years [49]. During the 1989 Loma Prieta earthquake, strong motion recordings captured a first mode frequency of 0.38 Hz. However, ambient vibration tests and low amplitude shaking measurements have consistently shown higher fundamental frequencies due to the absence of strong shaking. For example, forced vibration tests in 1985 reported a frequency of 0.58 Hz, and subsequent ambient vibration tests measured frequencies between 0.48 Hz and 0.54 Hz [50–52]. The decreased natural frequency of the building measured during the 1989 Loma Prieta earthquake, compared to ambient vibration tests, may be attributed to structural softening during strong shaking [53]. This phenomenon likely resulted from temporary changes in the building's stiffness due to the intense seismic shaking, which contributed to the observed lower frequency during the event.

The most recent ambient vibration test conducted by Çelebi et al. [50] measured a frequency of 0.48 Hz, and is consistent with what was captured using the MyShake app. The MyShake data recorded the building's natural frequency at 0.47 Hz for both axes (NS and EW). This demonstrates that MyShake's results are in good agreement with the most recent observations using traditional sensors.

Finally, Building 4 (SkyDeck), located at 2150 Shattuck Ave., Berkeley, is a 54-m tall lift slab structure characterized by its innovative design where floors are supported by twin reinforced concrete towers and suspended on tension hangers [54]. Measurements taken from the 13th floor using various smartphone models show fundamental frequencies ranging from 0.70 Hz to 0.85 Hz, with damping ratios between 0.08 and 0.12. These measurements were conducted under varying environmental conditions, including different wind speeds (ranging from calm to windy) and with phones in different states of attachment (some secured with tape and others not). The relatively high stiffness inferred from the lower frequency range, coupled with the specific energy dissipation properties indicated by the measured damping ratios, underscores the influence of the building's unique design. The variation in measured frequencies and damping ratios across different conditions suggests a complex interaction between the structural system and external factors, reinforcing the importance of detailed modal analysis in assessing the dynamic performance of such innovative structures.

It is important to note that the wind speed used in this study is the wind speed recorded at the nearest National Weather Service (NWS) station, which may not accurately reflect the local wind conditions at the building itself. For instance, the distance between the NWS station and Building 1 (Millennium Tower) is around 1.5 km. Since local topography and the built environment around the building can significantly alter wind flow, the wind speed at the building might differ, influencing its structural response and the effectiveness of excitation of its natural frequencies. While we primarily need the wind speed to be significant enough to excite the building's natural frequencies, the building's response to the wind is also influenced by its exposure and the wind direction. For instance, a building located in a densely urbanized area may experience different wind speeds and directions compared to an open-area NWS station. Therefore, even if the reported wind speed is sufficient, the actual impact on the building might vary depending on how directly the wind interacts with the structure. This can affect the signal-to-noise ratio (SNR) of the measurements along the building's principal axes, with potentially higher SNR in the axis more directly exposed to the wind. Understanding these factors helps improve the interpretation and reliability of the SHM measurements.

We measured the damping ratio based on the half-power bandwidth method by analyzing the PSD of the building acceleration measurements. The half-power bandwidth method is straightforward and easy to apply and allows for rapid estimation of the damping ratio [36]. It works well for single-degree-of-freedom (SDOF) systems and can be extended to multi-degree-of-freedom (MDOF) systems under certain conditions. However, the method can lead to significant errors when applied to MDOF systems, especially if the modes are closely spaced because mode coupling can affect the accuracy of the estimation. The accuracy of the half-power bandwidth method can also be affected by the frequency resolution of the measured data. Yu et al. [55] suggested that the PSD method is most effective for systems with low damping ratios. However, for structures with more complex damping properties or where the damping ratio varies significantly across modes or frequency, corrections or more advanced techniques might be required to enhance accuracy. Some studies suggest that using third-order corrections in the half-power bandwidth method could improve the accuracy of damping

estimates in such complex systems [56]. In our measurements of the damping ratios, the results (Table 1) show relatively consistent measurements across different buildings, floors, and smartphone models, with a slight variation arising due to factors such as sensor placement (taped or untaped) and building characteristics. For example, the damping ratios measured in the Millennium Tower show minimal variance between phones (e.g., 0.07 ± 0.001 vs. 0.07 ± 0.005), suggesting that the method worked well under these conditions. However, in cases such as Building 4 (SkyDeck), where the material and structural systems are different, the measured damping ratios varied more significantly (e.g., 0.09 ± 0.08 vs. 0.12 ± 0.04), indicating that mode coupling or measurement conditions may have introduced errors.

Our findings indicate significantly higher correlations between the waveforms for selected PSD records compared to the discarded ones (Fig. S7). Further, we suggest that bootstrapping-based hypothesis testing could be developed to examine the significance of these correlation values, enhancing our ability to determine the building's natural frequencies accurately. Overall, the correlation techniques used to extract the natural frequencies of the building affirm the reliability of the waveform recordings used for this study by cross validating the results obtained from the PSD method. For our small sample size of building heights, we found that the correlation values obtained from the MyShake recordings are generally higher for taller buildings (Building 1, Millennium Tower, Fig. 10) compared to shorter ones (Building 3, Pacific Park Plaza, Fig. S8). This is likely due to the higher signal strength and consistent vibrational modes present in taller structures, which exhibit lower natural frequencies and greater signal coherence. The higher correlation values for taller buildings indicate that the natural frequencies are more distinct and can be measured more reliably, enhancing the overall effectiveness of MyShake in these environments.

The study also revealed that by measuring the natural frequencies over time, it is possible to establish a healthy baseline for each building's structural condition. This baseline is crucial for detecting significant deviations that may indicate structural issues, such as damage or deterioration. Continuous monitoring and trend analysis can provide a dynamic view of a building's health, enabling proactive maintenance and safety evaluations. For instance, Williams et al., [21] studied the natural frequency variations of the Caltech Hall using 20 –years of data and showed variations in natural frequencies with an overall increase of 5.1 % in the east-west direction and 2.3 % in the north-south direction. They suggested that the unexpected stiffening, contrary to the typical softening observed in other buildings, highlights the complexity of soil-structure interactions and the influence of non-structural changes and micro-damage from earthquakes. Similarly, Astorga et al., [57] showed the reduction in the natural frequencies of a steel and reinforced concrete building in Japan over a period of 12-year. They observed that the natural frequencies of the building decreases continuously under a low-strain environment until a plateau is reached. This characterizes the continuous damage process with repeated dynamic loading forces conditioning the structure. Such insights were only possible due to the continuous recording of the building's response to ambient and seismic forces over an extended period. These case studies strongly support the implementation of similar long-term monitoring systems in other structures to establish a healthy baseline for each building's condition.

Despite the advantages, the automated natural frequency measurement technique used in this study has some limitations that could be addressed in future work. One notable limitation is that the technique is currently optimized to measure only the fundamental modal frequency and damping ratio of the building. Expanding the capability to capture higher modes of vibration and additional structural characteristics would significantly enhance the comprehensiveness of our SHM approach. Higher modes of vibration reflect more complex deformation patterns of a building that are not observable through the fundamental frequency alone. These modes can provide detailed information about the stiffness and mass distribution across the structure. Understanding these patterns helps in detecting localized damage and can improve the assessment of the building's overall structural integrity. Additionally, the accuracy of measurements can be influenced by environmental noise and sensor placement, both of which should be carefully considered and mitigated in future developments. Improving noise reduction algorithms and developing algorithms to deal with unknown sensor placement could further increase the reliability and precision of the measurements. Integrating advanced signal processing techniques, surrogate modeling approaches, and machine learning for data analysis could also help in distinguishing between structural responses and background noise, as well as enable rapid, scalable predictions of building dynamic properties based on smartphone recordings, thereby improving the overall effectiveness of the SHM system.

In addition to smartphones, recent advancements in low-cost MEMS-based accelerometers offer a promising alternative for structural monitoring in high-stakes environments such as schools, hospitals, and critical infrastructure. While their cost remains prohibitive for widespread deployment at a societal scale, these sensors are affordable enough to enable dense instrumentation in targeted, high-priority structures. Although their dynamic range and noise floor is comparable to that of smartphone sensors [8,12], the ability to operate continuously with dedicated power sources allows for uninterrupted long-term monitoring. Networks such as the CSN have demonstrated that, when appropriately deployed, low-cost MEMS accelerometers can reliably capture structural responses during seismic events [58,59] and perform reliable modal shape analysis for the building [59,60]. Moreover, the data quality and consistency from these sensors also make them suitable for applying traditional SHM methodologies, including finite element model updating and modal-based damage detection, thus facilitating the development of high-fidelity models for structural assessment and resilience planning. In contrast, the availability of smartphones running the MyShake app is typically limited to one or two devices per building, which constrains spatial coverage and makes modal shape estimation currently impractical.

In the domain of vibration-based diagnostics for complex building structures, distinguishing between global and local fault conditions presents a pivotal challenge. Global faults refer to damages that affect the overall structural integrity and dynamic behavior of a building, such as shifts in natural frequencies, which can be effectively monitored through Operational Modal Analysis (OMA) using smartphones. Local faults, on the other hand, are smaller, localized damage that may not significantly alter the building's overall dynamic response but can still compromise structural integrity, such as cracks or localized weakening of materials. Detecting these local defects using smartphones is challenging due to the limited number of sensors in a single building, which restricts comprehensive coverage for local defect identification. Additionally, the uncertainty in vertical elevation estimates further complicates the precise

detection of local faults. However, advancements in GPS technology that reduce vertical uncertainty, combined with an increased number of MyShake smartphones deployed within a building, could significantly enhance the ability to characterize local defects. By increasing sensor density and improving spatial data precision, it could be possible to achieve a more detailed understanding of a building's structural health in the future. Moreover, smartphones can be used as a preliminary screening tool to identify buildings that require further analysis with traditional sensors. This hybrid approach allows for initial identification of potential issues using the widespread availability and ease of deployment of smartphones, followed by detailed investigation using more precise traditional sensor networks, ensuring comprehensive structural health monitoring.

8. Conclusion

This study investigated the feasibility of using smartphone-based ambient vibration recordings to extract fundamental modal properties of buildings. The findings confirm that MyShake-enabled smartphones can reliably measure the fundamental frequencies and damping ratios of buildings under ambient conditions, particularly for taller structures with lower natural frequencies.

We demonstrated that reliable frequency measurements for tall buildings can be obtained even in low-wind speed conditions. However, shorter buildings require stronger dynamic loading forces to measure reliable fundamental frequencies. This finding highlights the potential for widespread structural health monitoring using readily available smartphone technology.

The focus on measuring fundamental frequencies using ambient vibration data captured by smartphones with the MyShake application illustrates a promising integration between traditional structural engineering practices and the advancements offered by modern technology. This approach leverages the scalability and accessibility of smartphone technology, facilitating continuous and efficient monitoring of structural health.

While the current approach targets fundamental mode identification, it lays the groundwork for future advances. These include the incorporation of advanced signal processing, machine learning, and surrogate modeling to improve noise robustness, extract higher-order modes, and enable rapid assessments across large building inventories. Such developments could greatly enhance the role of smartphone-based SHM in proactive maintenance and infrastructure resilience.

CRedit authorship contribution statement

Utpal Kumar: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization. **Savvas Marcou:** Writing – review & editing, Data curation. **Richard M. Allen:** Writing – review & editing, Supervision, Conceptualization.

Data and resources

The datasets generated and analyzed during the current study are not publicly available due to privacy and data usage agreements with participants, but some samples of the data are available from the corresponding author on request. The MyShake application is freely available for download on various smartphone platforms, which allows other researchers to replicate or extend this study in other locations.

Declaration of competing interest

This is the original work of the authors, and all authors have seen and approved the final version of the manuscript being submitted. The material described here is not under publication or consideration for publication elsewhere. The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jobbe.2025.112496>.

Data availability

Data will be made available on request.

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