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Integration of Seismic Interferometry and System Identification Techniques for Real-Time Structural Health Monitoring: Automated Detection of Shear-Wave Velocity Changes Using Skyscraper Data for Validation

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ABSTRACT: This study presents an integrated approach that combines seismic interferometry and system identification techniques for real-time Structural Health Monitoring (SHM), enabling the automated detection of changes in shear-wave velocity profiles for damage assessment. The methodology is validated using data from a 62-story residential skyscraper in San Francisco, one of the tallest buildings in the Western U.S., equipped with 72 uniaxial accelerometers across 26 floors. The building incorporates advanced structural components, including buckling-restrained braces, outrigger columns, and a tuned liquid damper to mitigate seismic and wind-induced responses. Data from the 2014 M6.0 South Napa and 2018 M4.4 Berkeley earthquakes, as well as ambient vibration recordings, are analyzed to establish baseline dynamic properties, including modal parameters, shear-wave profiles, and wave attenuation. We monitor wave propagation velocities, normal mode frequencies, and intrinsic damping through deconvolution interferometry, enabling real-time identification of structural stiffness changes. Shear-wave travel-time curves from deconvolution show reduced velocities below the 28th floor, coinciding with buckling-restrained braces, while higher velocities are observed above. This integrated methodology offers a robust framework for automated damage detection and real-time structural health assessment, demonstrating the potential to enhance the resilience and safety of high-rise structures during seismic events.

KEY WORDS: Structural Health Monitoring (SHM); Seismic Interferometry; System Identification; Shear-Wave Velocity; Damage Detection; High-rise structures.

1 INTRODUCTION AND BACKGROUND

Structural Health Monitoring (SHM) plays a crucial role in maintaining the safety and resilience of critical infrastructure, particularly in regions prone to seismic activity. High-rise buildings in seismically active zones such as the San Francisco Bay Area must withstand frequent and potentially severe seismic events. San Francisco, situated above an intricate network of active faults, including the San Andreas Fault, faces considerable seismic hazards, with the U.S. Geological Survey (USGS) forecasting a high probability of significant earthquakes occurring within the next few decades [1].

This paper explores the application of an advanced integrated SHM methodology to One Rincon Hill South Tower, a landmark 62-story, 195-meter-tall residential skyscraper in San Francisco, California. Recognized as the tallest residential building in California, the tower is instrumented with 72 uniaxial accelerometers strategically distributed across 26 floors, facilitated through collaborative efforts between the USGS National Strong Motion Project and the California Geological Survey's Strong Motion Instrumentation Program. Unique design features, including buckling-restrained braces (BRBs), an outrigger column system, a tuned liquid damper (TLD), and a robust, twelve-foot-thick mat foundation, are incorporated to enhance its resistance against seismic and wind-induced forces.

The study aims to validate an innovative real-time SHM system integrating seismic interferometry and system identification methods. This integrated approach aims to automate the detection of structural anomalies, specifically through monitoring changes in shear-wave velocities and wave attenuation characteristics. Validation is accomplished using data recorded during the 2014 M6.0 South Napa and 2018 M4.4 Berkeley earthquakes, alongside ambient vibration monitoring data.

Advancements in Structural Health Monitoring have increasingly focused on integrating sophisticated methods for more accurate and reliable damage detection. Modal analysis approaches, particularly Frequency Domain Decomposition (FDD), have become standard practice in determining fundamental structural properties such as natural frequencies, mode shapes, and damping ratios. These methods effectively identify changes indicative of structural deterioration or damage [2]-[3].

Seismic interferometry has emerged as an essential complementary approach within SHM, enabling the extraction of detailed structural parameters from seismic and ambient vibration data. The principle of seismic interferometry involves retrieving Green's functions between sensors, thereby providing insights into wave propagation velocities and intrinsic attenuation characteristics, independent of knowledge of the source excitation [4]-[5]. Among interferometric approaches, deconvolution interferometry is particularly beneficial in distinguishing between intrinsic structural attenuation and scattering attenuation, thereby significantly improving stiffness and damage detection accuracy within monitored structures [6]-[7].

Significant validation of deconvolution interferometry in SHM was conducted by Snieder and Safak [4], who accurately estimated structural wave velocities and intrinsic attenuation parameters in the Millikan Library, demonstrating notable

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advantages over traditional interferometric methods. Additional validation performed by Kohler et al. [9] in the Factor Building reinforced these findings, indicating a robust potential for application in real-time SHM scenarios.

However, traditional interferometric and modal identification methods independently exhibit limitations, notably insufficient sensitivity to localized stiffness reductions, which are critical for early-stage damage detection. To address these challenges, recent research highlights the importance of integrating seismic interferometric techniques with sophisticated system identification methods, significantly improving the accuracy and reliability of real-time SHM systems [6],[8].

This study builds upon previous work by integrating seismic interferometry methods, specifically modal identification techniques, which are validated using extensive seismic datasets from an extensively instrumented skyscraper. This innovative integration significantly enhances SHM capabilities, particularly for high-rise structures subjected to dynamic seismic loads, enabling timely detection and accurate characterization of structural health, which is crucial for improving resilience and minimizing post-earthquake recovery periods.

2 METHODOLOGY

2.1 Seismic Instrumentation and Data Collection

The seismic instrumentation of the One Rincon Hill South Tower comprises a comprehensive network of 72 uniaxial accelerometers strategically distributed across 26 floors (Figures 1–4).

Figure 1. 195m skyscraper in San Francisco (photo is courtesy of Magnusson Klemencic Associates).

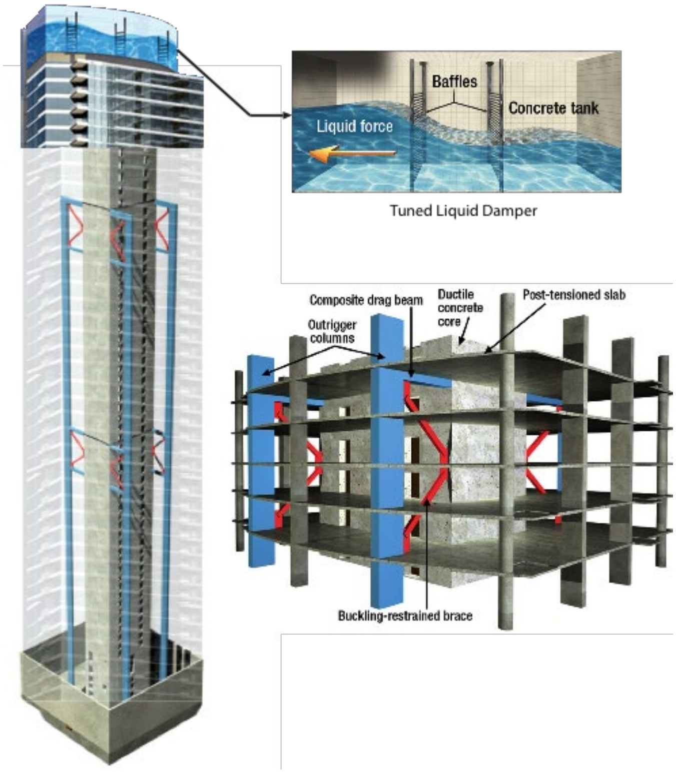

Figure 2. The primary seismic load-resisting system with concrete core and outriggers comprising buckling restrained braces. The water tank located at the roof level serves as a tuned liquid damper to mitigate wind forces (Figures modified from Magnusson Klemencic Associates).

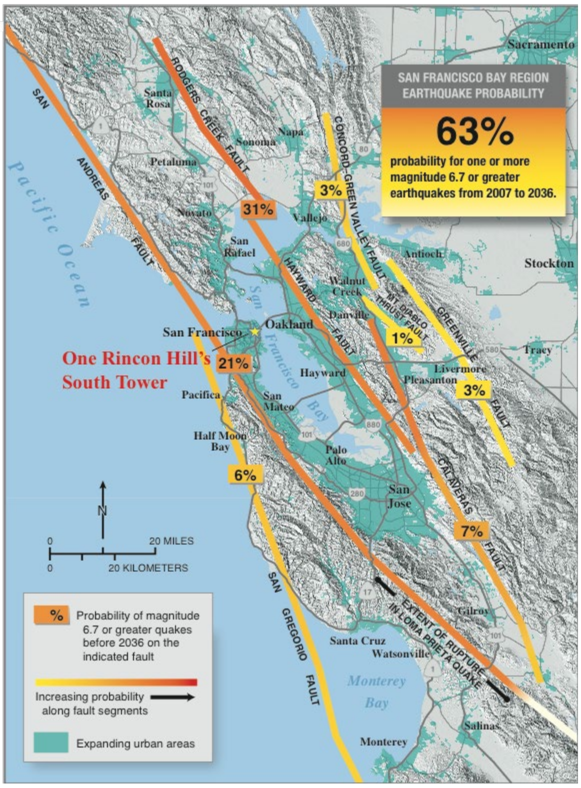

Figure 3. San Francisco Bay Area earthquake faults. The star sign indicates the location of the 195m skyscraper. (modified from http://earthquake.usgs.gov/regional/nca/ucerf/).

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This dense array was meticulously designed and installed by the USGS's National Strong Motion Project in collaboration with the California Geological Survey's Strong Motion Instrumentation Program. Particular emphasis was placed on instrumenting floors equipped with critical structural elements, including buckling-restrained braces (BRBs) connecting the building to the outrigger systems at floors 26–32 and 52–55. Additional sensors placed at the base and roof levels facilitate the measurement of vertical accelerations, which are essential for quantifying the rocking motion induced by seismic excitation.

The recorded data include responses to two significant earthquakes: the 2014 M6.0 South Napa earthquake (epicentral distance of approximately 48.7 km) and the 2018 M4.4 Berkeley earthquake (epicentral distance of approximately 15.6 km). Ambient vibration measurements were also captured, providing a baseline for comparison of structural properties.

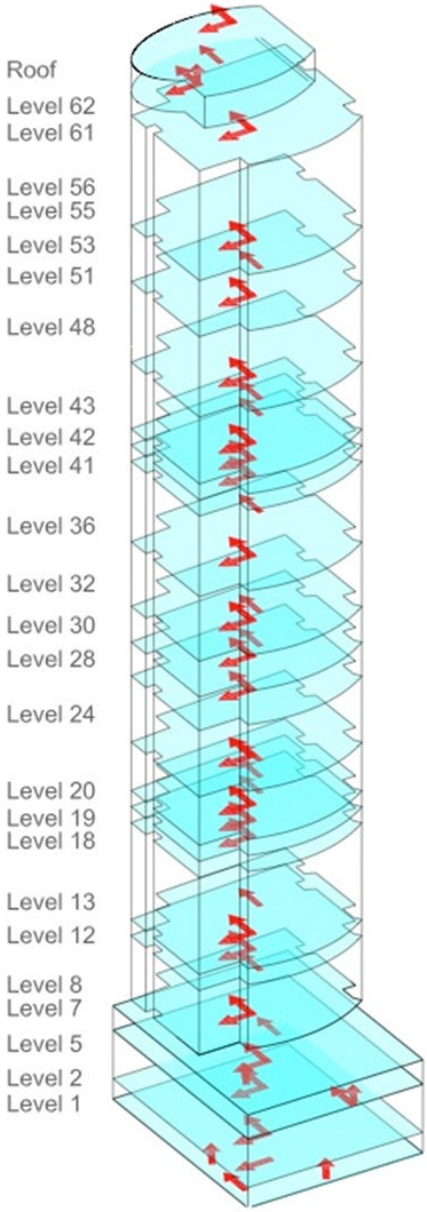

Figure 4. Sensor layout. Red arrows indicate the locations and the directional sensitivity of the accelerometers.

2.2 *Seismic Interferometry and System Identification Framework*

The methodology integrates seismic interferometry with system identification techniques for real-time structural health assessment. Seismic interferometry, particularly through the deconvolution approach, allows extraction of the structure's impulse response function (IRF) independent of external excitation sources. The governing equation for waveform deconvolution interferometry, adapted for building structures, can be expressed as in Eq. (1).

$$D(\omega, z) = \frac{U(\omega,z)}{U(\omega,H)} \quad (1)$$

where $U(\omega, z)$ is the recorded seismic response at a specific height z, and $U(\omega, H)$ represents the recorded response at the reference level H, typically the roof or base of the structure.
Eq. (1) may become ill-conditioned when the denominator approaches zero. To avoid this condition, the following regularized format is used as the estimator of deconvolution:

$$D(z, z_a, \omega) = [u(z,\omega)u^*(z_a,\omega)]/[|u(z_a,\omega)|^2 + \varepsilon\langle|u(z_a,\omega)|^2\rangle] \quad (2)$$

where superscript "*" denotes the complex conjugate, ε is the regularization parameter (ε=0.01 is used here, based on prior experience), and $\langle|u(z_a,\omega)|^2\rangle$ is the average power spectrum of $u(z_a,\omega)$.

System identification was executed using Frequency Domain Decomposition (FDD), an established modal analysis technique that effectively identifies modal parameters from ambient and seismic-induced vibrations. FDD facilitates modal parameter estimation by decomposing the spectral density matrices of the recorded accelerations into singular values, thus accurately identifying natural frequencies, mode shapes, and damping ratios of the structure [1]-[2].

The integrated approach involves calculating wave propagation velocities, normal mode frequencies, and intrinsic damping characteristics from the IRFs obtained via deconvolution interferometry. Shear-wave velocity profiles are computed explicitly by analyzing the propagation times of upgoing and downgoing shear waves through different building sections. Changes in these profiles effectively indicate stiffness alterations, potentially signifying structural damage or degradation [3],[5].

2.3 *Analysis Procedures*

Analysis began by establishing baseline modal parameters using ambient vibration data. Subsequently, earthquake data from the South Napa and Berkeley events were analyzed to quantify structural response under significant seismic loading conditions. This comparative assessment between baseline and event-specific modal parameters allowed for the precise detection and characterization of structural changes. Wave propagation velocities, intrinsic damping, and attenuation characteristics were estimated in real-time using advanced computational procedures integrating seismic interferometry and system identification.

Wavefield decomposition techniques were also utilized, providing causal (forward-time) and acausal (time-reversed) waveform comparisons. Discrepancies between these

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waveforms facilitated precise estimation of intrinsic attenuation, as scattering attenuation remains invariant under time reversal, thus isolating intrinsic material damping characteristics effectively [3],[7].

The methodological rigor and integrated analytical procedures presented herein establish a robust framework for accurate real-time monitoring and damage detection capabilities in high-rise buildings, particularly under seismic excitations.

3 RESULTS AND DISCUSSION

3.1 Baseline Dynamic Properties

Baseline modal properties of the One Rincon Hill South Tower were established using ambient vibration data and verified with earthquake-induced vibrations from the 2014 South Napa and 2018 Berkeley earthquakes. Modal analysis using Frequency Domain Decomposition (FDD) revealed the first five fundamental modes within the frequency range of up to 6 Hz. Identified modes included distinct bending and torsional behaviors. Specifically, the fundamental bending modes were clearly observable at frequencies below 1 Hz, consistent with expectations for a high-rise structure of this scale. Notably, ambient vibration data revealed subtle torsional modes, which were less prominent in the earthquake response data, indicating nonlinear behavior activated by seismic events.

3.2 Shear-Wave Velocity Analysis

Utilizing deconvolution interferometry, distinct shear-wave velocity profiles were extracted, displaying apparent variations across the structural height of the building. Figures 5-6 and Table 1 illustrate these variations, which were particularly evident in areas around structural transitions, such as the presence of buckling-restrained braces and outrigger systems. Below the 28th floor, significantly reduced shear-wave velocities were consistently observed, correlating directly with the increased structural flexibility imparted by the BRBs. In contrast, increased velocities above this level underscored the effectiveness of outrigger columns and tuned liquid damper systems in enhancing structural rigidity. This spatial variation in wave velocity effectively delineates stiffness transitions, which are critical for accurate real-time monitoring and damage detection.

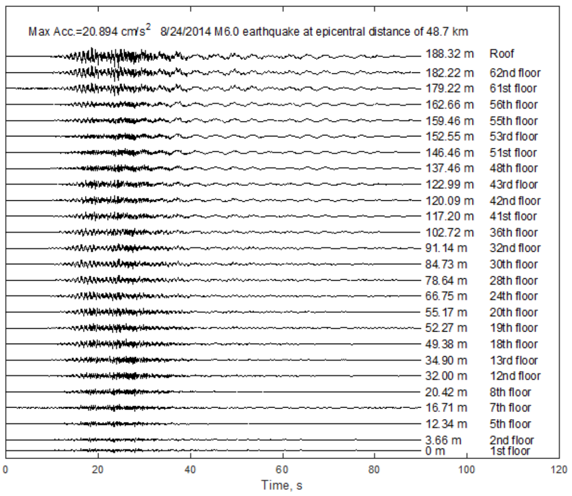

Figure 3. Recorded east-west waveforms from the 2017 M6.0 South Napa earthquake at an epicentral distance of 48.7 km.

Propagating waves from the first floor to the roof show amplification in the order of 4.2. The floor numbers and their corresponding height relative to the ground (1st floor) are depicted; the maximum roof acceleration is 20.894 cm/s^2.

Table 1. Modified Shear-Wave Velocity Profiles.

Floor Range	Average Shear-Wave Velocity (m/s)
Below 28	210
28 to 52	350
Above 52	450

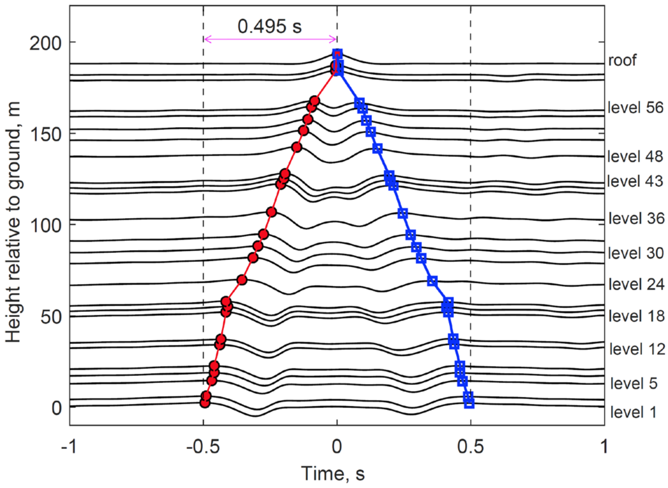

Figure 4. Deconvolved waveforms, calculated from the 2014 Napa earthquake east-west direction acceleration time series, are plotted as positive and negative amplitudes for each instrumented floor over time. The frequency range of the waveforms is 0–4 Hz.

3.3 Intrinsic Damping and Attenuation Characteristics

The damping properties of the structure were quantitatively assessed using the impulse response functions (IRFs) derived from deconvolution interferometry. Results indicated intrinsic damping ratios of approximately 4.4% in the east-west direction and 3.7% in the north-south direction. These values align with expected damping ranges for high-rise buildings, reflecting effective energy dissipation during seismic excitation. Furthermore, wavefield decomposition analysis clearly distinguished between causal and acausal waveforms, allowing precise estimation of intrinsic attenuation. Variations in these characteristics across different building elevations indicated localized stiffness and damping alterations potentially associated with structural degradation or minor damage [3],[7].

These detailed results demonstrate the efficacy and reliability of the integrated SHM methodology proposed herein, providing a robust analytical framework capable of effectively detecting and localizing structural changes.

3.4 Discussion

As demonstrated in this study, integrating seismic interferometry with advanced system identification techniques

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significantly enhances real-time Structural Health Monitoring (SHM) capabilities, particularly in detecting subtle and localized changes in structural stiffness. The results demonstrate the clear advantages of this integrated methodology, particularly in terms of sensitivity and precision in detecting shear-wave velocity variations associated with structural anomalies.

The observed shear-wave velocity reductions below the 28th floor are particularly noteworthy, correlating directly with regions containing buckling-restrained braces (BRBs). These velocity reductions reflect structural flexibility intentionally designed to absorb and dissipate seismic energy. Conversely, higher shear-wave velocities identified above this zone demonstrate the significant rigidity provided by outrigger columns and tuned liquid dampers (TLD). Such explicit distinctions in velocity profiles serve as effective diagnostic markers, facilitating the precise localization of stiffness changes that potentially indicate structural deterioration or damage initiation.

The intrinsic damping characteristics obtained via deconvolution interferometry and wavefield decomposition provided precise estimates aligning closely with theoretical predictions and empirical data for high-rise structures. The ability to differentiate between intrinsic damping and scattering attenuation effects substantially improves over traditional SHM methodologies, which frequently fail to distinguish between these phenomena, thereby limiting adequate diagnostic accuracy.

However, some limitations of the current approach should be acknowledged. Specifically, assumptions of linear-elastic behavior under ambient vibrations may inadequately represent the structure's nonlinear response during significant seismic events. Enhancing the methodological framework to better account for nonlinear dynamics through advanced system identification approaches could substantially increase diagnostic robustness and reliability.

Moreover, practical considerations for real-world applications, such as computational demands, processing speed, and sensor robustness under extended environmental exposure, remain critical. Addressing these concerns through improved sensor technologies and optimized real-time computational algorithms is crucial for the practical implementation and widespread adoption of structural health management systems.

4 CONCLUSIONS AND FUTURE RESEARCH

4.1 Conclusions

This study comprehensively evaluated an integrated methodology combining seismic interferometry with system identification techniques, validated using extensive data from the instrumented One Rincon Hill South Tower. The methodology demonstrates robust capabilities for the automated and accurate real-time detection of structural stiffness variations through precise estimations of shear-wave velocities and intrinsic damping.

The major conclusions drawn from this research are:

- Enhanced Damage Detection Sensitivity: The integrated seismic interferometry and system identification approach significantly improves the detection and localization of subtle stiffness reductions, which are essential for timely structural health assessments in high-rise buildings in seismic-prone regions.
- Effective Characterization of Structural Components: The methodology accurately delineated shear-wave velocity profiles corresponding explicitly to structural features, such as BRBs, outrigger columns, and tuned liquid dampers. This precise characterization offers actionable insights into structural integrity and performance under seismic conditions.
- Improved Damping and Attenuation Estimations: Intrinsic damping and attenuation properties were effectively isolated from scattering effects, significantly enhancing the reliability and diagnostic accuracy of structural condition assessments.
- Identification of Linear versus Nonlinear Behaviors: The study successfully differentiated structural responses induced by ambient conditions (linear-elastic) from those triggered by seismic events (nonlinear behaviors). Highlighting these differences underscores the necessity for continued methodological refinement in capturing comprehensive structural dynamics under seismic loads.

4.2 Future research

- Extending the developed integrated methodology to diverse structural types and construction materials broadens its applicability and effectiveness.
- Refining computational algorithms to ensure faster, more resource-efficient real-time structural analyses suitable for practical applications.
- Developing advanced nonlinear interferometric and system identification techniques capable of fully characterizing complex structural behaviors during significant seismic events.

Ultimately, the results and methodologies presented significantly advance the discipline of real-time structural health monitoring, promising substantial improvements in structural safety, resilience, and post-earthquake functionality. The presented method could make a significant contribution to many of the current structural engineering applications related to assessing structures under seismic effects, e.g., [10]–[44].

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