DOI: 10.3217/978-3-99161-057-1-186

On the use of 6C seismic station for bending-to-shear and torsional building response assessment.

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ABSTRACT: To understand the behavior of healthy structures and the changes to their condition over time, it is imperative to perform experimental analysis of existing civil engineering structures. Development of novel sensors measuring rotations enable to directly measure important components of the system parameters, as they provide additional information on the structural response. Long-term monitoring of existing structures using 6C sensors – 3C translation and 3C rotation, enables a more in-depth analysis of the system parameters; frequency, modeshape and damping. Specifically, the translation-based characterization of the torsional mode can be enhanced through direct measurement of the torsional angle, center of torsion and more precise frequency extraction. Furthermore, the distinction between shear and bending can be analysed through the ratio of angle and deflection, instead of using proxies like frequency ratios or shear wave velocity. In this study, we analyse how using 6C datasets for structural characterization of high-rise buildings provide further information to understanding the system parameters and their variations over time. We find that the rotational components significantly contribute to the understanding of the vibration behavior and thereby propose to include 6C sensors to enhance the characterization of structures.

KEY WORDS: 6C dataset; structural characterization; shear; bending; rotation; translation; system property variation.

1 INTRODUCTION

Analyzing seismic data to observe the dynamic behavior of buildings is a well-established approach in structural monitoring. Traditionally, this has relied on accelerometers and seismometers to capture translational motion. Recently, sensors capable of detecting rotational motion have expanded these capabilities [1]. Combining rotational and translational data provides more details on the structures behavior. Collocating 3 components rotation and 3 components translation improves the frequency resolution for torsional modes, and enables the determination of 6C mode shapes at the roof level with minimal sensor footprint, as shown in [2].

A key analysis is to determine a baseline for a healthy structure, concerning the system properties—like resonance frequency, damping, mode shapes, and waveform-based signal statistics [3]. In the absence of damage, these features are expected to stay consistent over time. Unless environmental parameters such as temperature, wind, or precipitation change, then they can temporarily influence the system behavior [4], [5]. Torsional modes often respond differently to environmental variations compared to translational modes, as shown in [6].

The translational modes of structures can be approximated through a shear or Euler-Bernoulli beam [7]. However, real structures are a combination of both. The Timoshenko beam theory incorporates both bending and shear [8], and has been applied to real structures in [9], [10]. Multiple methods exist to assess the prevailing regime - shear or bending, including frequency ratios [8], interferometric determination of shear velocity [8], and interstory drift analysis using sensor arrays [9]. Structural damage can alter stiffness, mass, or damping, which in turn modifies the curvature of the resonance mode shapes. Monitoring the variation of a mode shape between bending and shear thus provides critical insights to a structures health [3].

The torsional modes are influenced by the eccentricity of the structure - which exists when the center of mass and center of rigidity do not coincide and the center of torsion. Due to inherent asymmetries in the building design or construction, all buildings display some torsional motion, which is a key factor in seismic damage. Therefore, changes in torsional response are vital to track for structural health monitoring.

This work investigates how 6C measurements can enhance structural characterization and monitoring, specifically for shear-to-bending and torsional response.

2 SENSORS AND EXPERIMENT SET-UP

There are a handful of buildings that have been instrumented for continuous 6C monitoring such as the high-rise building TAIPEI101 in Taiwan [10]. Where two 6C stations are located on the 90th floor comprising of an Eentec R1 rotation sensor and a Kinemetrics accelerometer each. Eentec R1 rotation sensor has a sensibility of $1.2 \cdot 10^{-7}$ rad/s which is frequency dependent and is sensitive to temperature [11]. Another common rotation sensor is the blueSeis-3A [12] with a sensitivity of $2.5 \cdot 10^{-8}$ rad/s from DC to 50 Hz. The blueSeis-3A was used to monitor the high-rise building Prime Tower in Switzerland for 1.5 years [2]. Recently high-quality 6C inertial

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measurement units have been assembled specifically for structural health monitoring. The sensor self-noise of the rotational sensor is at $1.5 \cdot 10^{-6}$ rad/s, therefore depending on the vibration amplitude, not always low enough for ambient noise, but low enough for active experiments [13]. The optimal location for a rotation sensor on a building is generally at the top floor, where the amplitude is the largest and an approximate modeshape can be extracted. On bridges this location is still an open question due to unresolved boundary conditions and location of maximum amplitude for rotational motion.

3 METHODS

In this study, we analyze the ratio between the horizontal rotation angle and deflection as a proxy for the vibration regime of high-rise buildings. Additionally, we are investigating the ratio between torsion angle and the displacement to extract the center of torsion.

The amplitudes of rotation and translation for each mode can be estimated either through the simple power spectral density (PSD) peak picking method or a more sophisticated method such as the stochastic subspace identification. Either way it is imperative that the methods are applied to the rotation angle and displacement directly and not the classic rotation rate and acceleration timeseries. As the derived ratio needs to be in the units of rad/m. Additionally, the relative amplitudes between rotation and translation need to be kept and a normalization as is often applied for mode shapes would have to be applied to all 6 components in the same way.

3.1 Ratio for shear-to-bending response

For the shear-to-bending response analysis the ratio between the rotation angle and deflection is calculated by simple division. For a symmetric quadratic building where the walls are oriented along the North-South axis the translational modes would either be in East or North direction. To analyse the East bending mode, the rotations around North are divided by the deflection in East. For the North bending mode, the rotations around the East are divided by the deflection in North.

3.2 Ratio for center of torsion

For an analysis of the torsional mode concerning the center of torsion the ratio between the vertical rotation angle and the horizontal translation is calculated. The horizontal translation is highly dependent on the location of the 6C station on the floor. At the center of torsion almost no displacement will occur, while there will be more translation away of the center of torsion. So, in theory one can estimate the torsional ratio by dividing the torsional angle through either the North, East or total horizontal displacement. A change of this ratio will mean a change of the center of torsion.

3.3 Variation of Ratio

It is expected that the ratio for both the shear-to-bending response as well as the center of torsion will vary due to environmental and operational changes. These are for example; temperature, humidity, air pressure, wind, rain and activation of a tuned mass damper. However, it is expected that an earthquake could influence the ratio similar to the modal frequencies, that often feel a drop and consecutive healing effect. Any permanent change of the ratio could hint at damage and would need to be investigated.

4 CONCLUSION

This study presents a new method based on the ratio between rotation angle and deflection. This ratio contains information on the mode shape, and thus the overall vibration regime. Here it is introduced to analyse 1) if a structure is in shear or bending, 2) where the center of torsion is for a structure and 3) why this ratio varies over time.

6C datasets enable the evaluation of vibration regimes in high-rise structures. However, the results depend strongly on accurate sensor placement, sensor quality, and the ability of sensors to remain unaffected by external influences aside from the measured motion.

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