Chapter 12
System Identification of a 10-story Cold-Formed Steel Building: Systematic Study Considering Sensor Distribution and Changes in Ambient Conditions

Shokrullah Sorosh, Jiachen Zhang, M. Khalid Saifullah, Derek Skolnik, and Tara C. Hutchinson

Abstract A 10-story cold-formed steel (CFS) building was constructed and tested on the six-degree-of-freedom Large High-Performance Outdoor Shake Table at UC San Diego (NHERI@UC San Diego). The primary objective of this testing program was to evaluate the seismic performance of a building with steel-sheathed shear walls beyond the current code height limit. The test specimen was also detailed with various nonstructural components and systems, including 9 stories of prefabricated steel stairs with drift-compatible connections, a fire sprinkler system with horizontal and vertical runs, rigid and flexible gas pipes, and rooftop equipment. These subsystems increased the fidelity of the specimen and its overall potential to capture true-to-field functional buildings. Prior to the seismic testing phase, the building's response under ambient conditions was recorded using various sensor systems and networks, including six rapid-deployment triaxial accelerographs. The unique combination of portability (wireless), high-fidelity (24-bit resolution), and precise time-synchronization (GPS timestamp) of these sensors allowed for convenient and speedy data collection prior to the seismic test phase. Using this pre-test data, this paper discusses the application of several output-only system identification techniques, including conventional Power Spectral Density (PSD) analysis, Frequency Domain Decomposition (FDD), and Data-driven Stochastic Subspace Identification (SSID), to determine the building's modal characteristics under ambient conditions. Observations regarding the SI results are presented, and the variation in the building's modal characteristics under changing ambient conditions is evaluated.

Keywords System identification · Dynamics · Ambient vibration · Shake table test · Operational modal analysis

Introduction

Recently, a 10-story cold-formed steel building, referred to as CFS10, was tested on top of the six-degree-of-freedom Large High-Performance Outdoor Shake Table (LHPOST6) at UC San Diego, see Figure 1a. This landmark building specimen measured 30.5 m in height and 6.86 m × 11.58 m in floor plan. The lateral force resisting system of this test specimen was designed with steel-sheet-sheathed shear walls. The primary intention of this test effort was to test a cold-formed steel-framed building with steel-sheet-sheathed shear wall beyond the current code (ASCE 7-22 [1]) height limit of 19.8 m. The building was subjected to a total of 18 earthquake motions, scaled to various risk-targeted hazard levels [2]. Hutchinson et al. [3] provide an overview of the building performance under the seismic test phase, while Singh et al. [4] summarize the structural design details of this building. In addition, this building featured various nonstructural components and systems, including a 9-story stair tower [5, 6], fire riser and sprinkler systems, windows, gas pipes [7], and roof-mounted mechanical equipment with various attachment details [8].

Shokrullah Sorosh · Jiachen Zhang · Tara C. Hutchinson
Department of Structural Engineering
University of California San Diego, La Jolla, CA
e-mail: ssorosh@ucsd.edu; j-charlie-zhang@ucsd.edu; tara@ucsd.edu

M. Khalid Saifullah · Derek Skolnik
Kinemetrics Inc., Pasadena, CA
e-mail: mks@kmi.com; das@kmi.com

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Numerous studies have investigated the use of system identification techniques to determine the modal characteristics of test structures under white noise base excitation or ambient conditions [9–12]. The primary objective of the present study was to identify the fundamental modal characteristics of the test specimen using ambient vibration data collected prior to the seismic testing phase. This step is essential for validating numerical simulation tools before conducting seismic tests. It is worth noting that no discussion of the finite element model validation is included in this paper. Zhang et al. [2] provide a detailed discussion on the evolution of the test protocol throughout the seismic testing phase of the CFS10 program. The finite element model of the building plays a crucial role in the ground motion iteration and scaling process. Therefore, identifying the modal characteristics of the building using ambient vibration (AV) data prior to the seismic test phase is critical for ensuring confidence in the finite element model results. The use of portable wireless-based sensors is feasible and convenient to conduct such a study, as it renders an efficient strategy for quickly providing response data. Alternatively, wired sensors would be installed within the building specimen, a highly time-consuming effort. In this study, six portable tri-axial accelerograph units were deployed to collect sufficient data to characterize the first three modal responses of the 10-story building. The vibration data was recorded for a duration of 23 hours and 35 minutes with 200 samples per second (SPS). With 200 SPS, the Nyquist frequency is 100 SPS, which is far above the range of interest for building modal characteristics. The deployment strategy was varied, considering various horizontal and vertical placement options, though the present article focuses on a sample of these results with one strategic layout. Results herein focus on documenting the change in building modal characteristics under varying ambient conditions.

Instrumentation

The acceleration responses of CFS10 under ambient conditions were recorded using six tri-axial accelerographs. These accelerographs were of model ETNA 2 with 3 sensor channels with a high fidelity internal EpiSensor triaxial deck, 24-bit resolution, and 155 dB+ dynamic range. As shown in Figure 1b, the sensors in the present discussion were placed at the northeast and southwest corners of the building at Levels L3, L7, and L11/roof. These locations along the height of the building were particularly chosen to avoid the modal nodes and to capture flexural dominant and torsional modes. In addition, the ambient conditions, such as temperature, humidity, and wind speed, were recorded using a weather station installed on the control building at the south side of the CFS10. Furthermore, the weather data were retrieved from Elliot station of the National Oceanic and Atmospheric Administration (NOAA) [13], which is located approximately 1.6 km southeast of the CFS10.

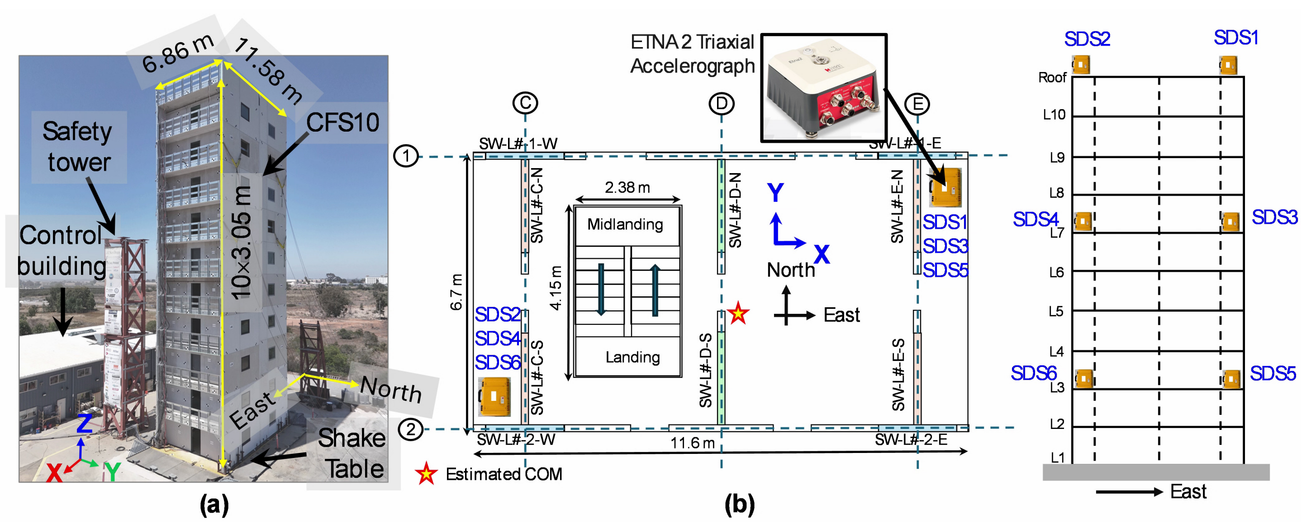

Fig. 1 (a) Isometric view of CFS10, and (b) instrumentation plan (SDS: Serial Data Stream)

Ambient Vibration Data

Data collection with the sensor deployment plan shown in Figure 1b began at 15:00 local time on April 28 and ended at 14:35 local time on April 29. Figure 2a shows the ambient conditions recorded during this period, based on measurements

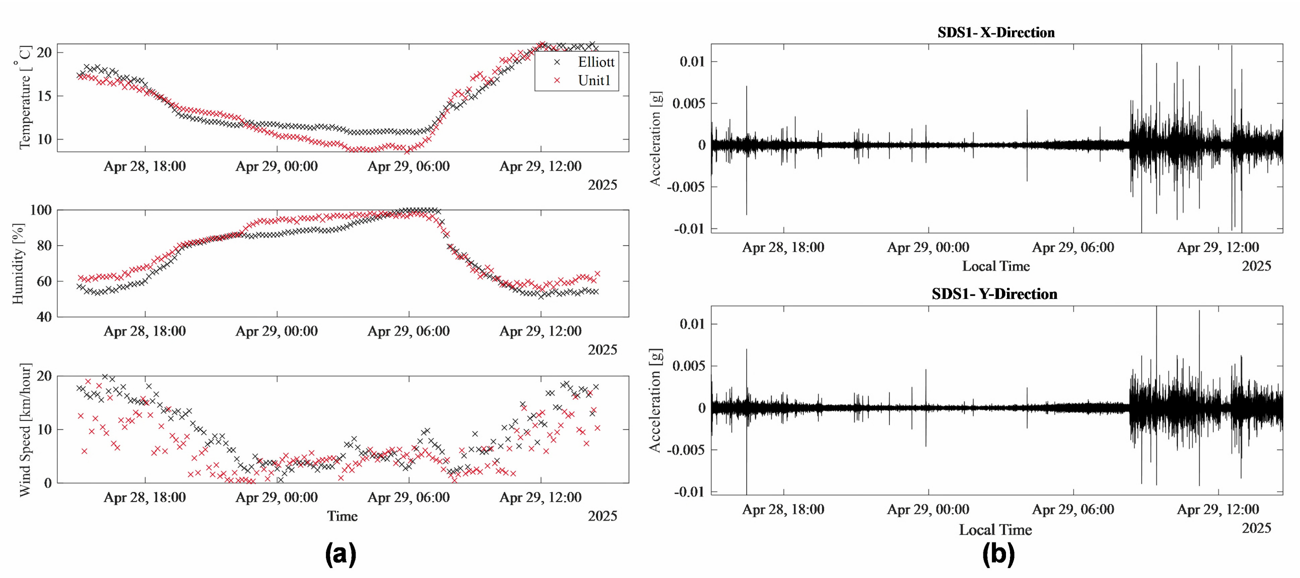

Fig. 2 (a) Ambient conditions and (b) acceleration time series during data collection with sensor deployment plan shown in Figure 1b. (Note: local time is based on Pacific Daylight Time (PDT))

from both the Elliot station (ground surface sensor) and the sensor attached to the control building (approximately 9m from ground level). The weather data from the two sources show good agreement, with some minor variations expected due to spatial differences between the stations. Figure 2b shows the acceleration time series in the X and Y directions recorded by sensor SDS1, located at the northeast corner of the building on the roof. In general, larger acceleration amplitudes are seen during daytime hours, primarily due to human activity in the building during ongoing cable and sensor installation. In addition, the wind speed during the daytime was approximately two to three times larger than at nighttime. The contribution of wind-induced loading on the lateral mode excitation of buildings with enclosed exteriors is significant.

Identified Modal Parameters

In this study, the vibration frequencies of the CFS10 building were identified using three output-only system identification techniques. The first method was based on the power spectral density (PSD) analysis, where the vibration frequencies were determined from the peaks of the PSD of the acceleration time series computed using Welch's method [14]. In addition, the Frequency Domain Decomposition (FDD) [15] and Stochastic Subspace Identification (SSID) [16] techniques were used to estimate the building's modal characteristics, including vibration frequencies and damping ratios. It is noted that, prior to running the system identification analyses, the acceleration time series were baseline corrected and filtered using a 4th-order Butterworth bandpass filter with cutoff frequencies of 0.075 Hz and 50 Hz. Figure 3a shows the acceleration time histories recorded at the northeast corner of the roof of the building by the SDS1 sensor during the first five minutes of data collection (i.e., April 28, 15:00-15:05 PDT). The corresponding PSD of this window is shown in Figure 3b, where each peak in the PSD identifies a vibration mode. The vibration frequencies identified from the SSID and FDD methods are shown by vertical dashed and solid lines, respectively. The frequencies estimated from the three methods show a good agreement.

The FDD and SSID techniques were used to identify the modal parameters throughout the duration of the deployment using continuous non-overlapping 5-minute data segments. Figure 4 shows the identified vibration periods and corresponding damping ratios for the first three vibration modes of the building during this deployment period. The first vibration mode is a flexural-dominant mode in the Y direction with a period ranging from 0.55 to 0.57 seconds. The second mode is a flexural-dominant mode in the X direction with a period between 0.53 and 0.55 seconds. The torsional mode is the third vibration mode with a period ranging from 0.37 to 0.38 seconds. As shown in Figure 4b, the damping ratios corresponding to these modes were generally estimated between 0.5% and 2%. A comparison between the identified vibration periods shown in Figure 4a and the temperature variation shown in Figure 2a demonstrates a gradual decrease in ambient temperature from approximately 18°C during the day to 9°C at midnight, accompanied by a slight reduction in the building's flexural mode period from 0.545 s during the day to 0.535 s at midnight in the X direction, and from 0.565 s during the day to 0.555 s at midnight in the Y direction. Although this 0.01-second change in the building period is relatively small, the observed

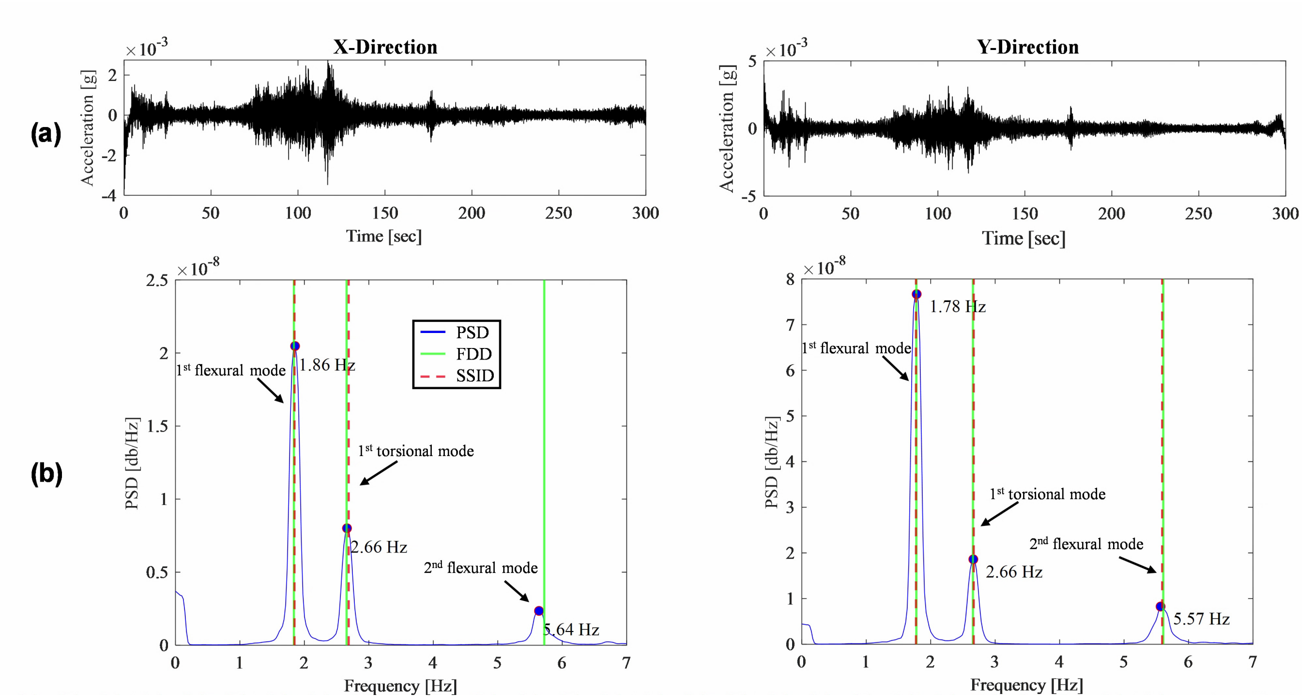

Fig. 3 (a) Acceleration time series from SDS1 for the first time window (April 28, 15:00-15:05 PDT), and (b) corresponding power spectral density with identified modal frequencies using each of the three studied methods highlighted

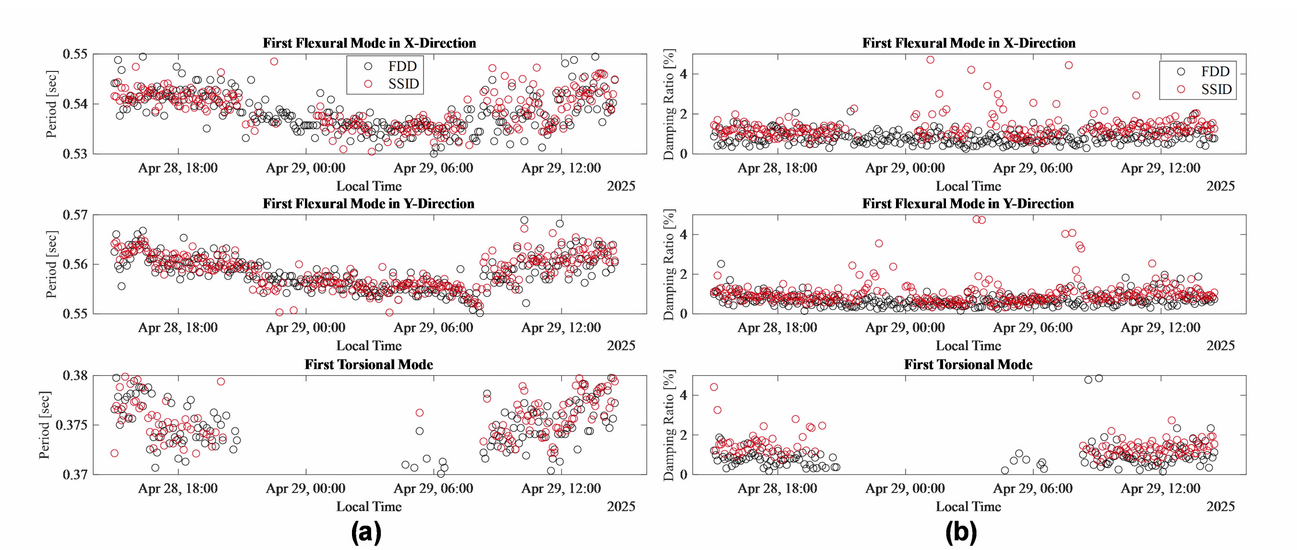

Fig. 4 (a) Identified vibration period (b) damping ratios of CFS10 corresponding to the first three fundamental modes

trend shows that the building becomes slightly stiffer under colder conditions. In addition, this reduction in building period is partially due to lower wind speed during the night as compared to wind speed during the daytime. An increase in humidity would also increase the mass of some buildings, such as wood-framed buildings, but cold-form-steel-framed buildings are expected to be less affected by the humidity level. Furthermore, observing the torsional mode shows that both FDD and SSID identification techniques failed to identify the modal parameters during the calmer hours of the day, which were approximately between 8:00 PM PDT April 28 and 8:00 AM PDT April 29. During this period, the wind speed was relatively low, ranging from about 2 to 4 kilometers per hour.

Figure 5 shows a comparison of identified modal parameters based on the FDD and SSID methods, along with a histogram of the distribution of identified modal parameters. It is noted that the histogram is developed based on a total of 283 samples. Observing the period's scatter plots, the data points are observed closely around the diagonal reference line. Both scatter plots and histograms show a strong agreement between FDD and SSID in estimating the vibration periods. However, the damping ratios show relatively larger scatter, particularly for the X and Y directions, suggesting larger discrepancies in damping ratios obtained using the two methods. Nonetheless, these results show the robustness of both methods in identifying the vibration period while also emphasizing the discrepancies in estimated damping ratios, which are typically very sensitive to noise and system identification modeling assumptions, thus an anticipated observation given the use of AV-data.

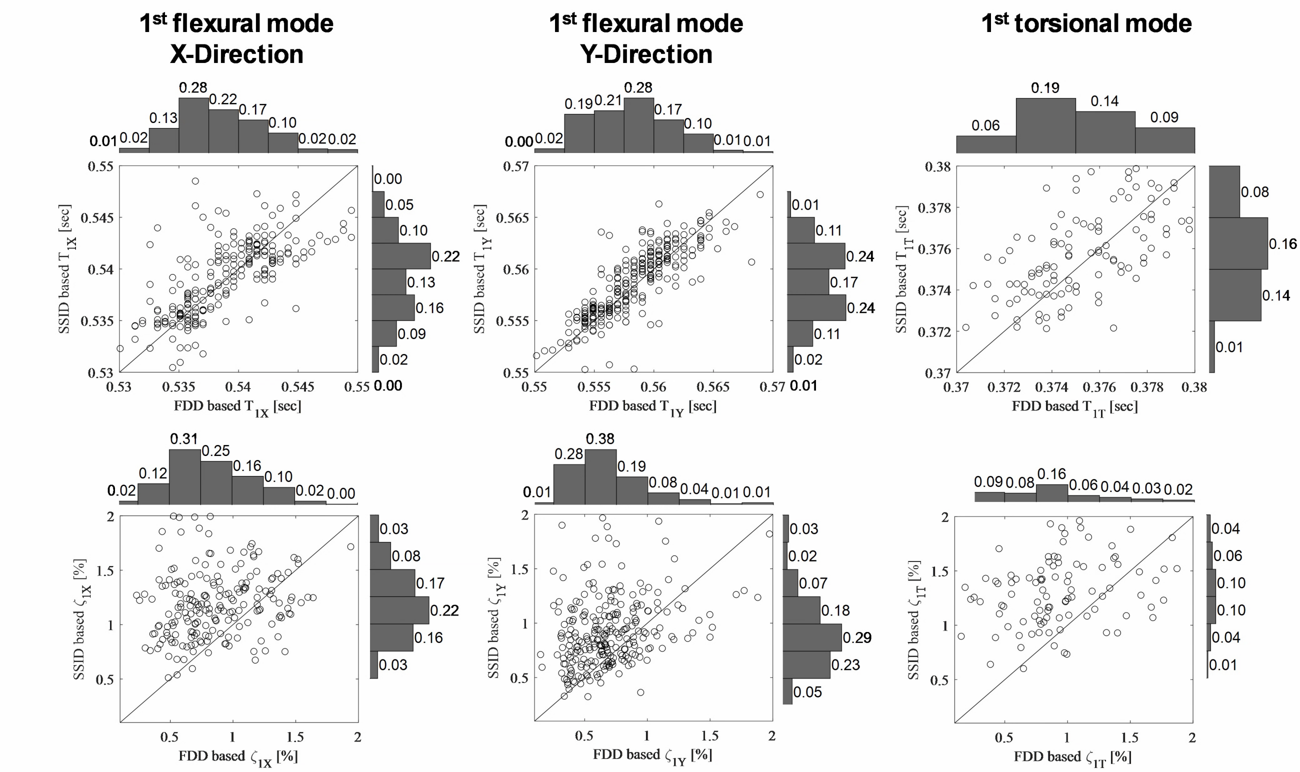

Fig. 5 Comparison of identified period and damping ratios estimated using SSID and FDD (Note: (1) for each case, a total of 283 windows of 5-minute length AV data is considered (total test duration was 23 hours and 35 minutes), and (2) histogram frequency bins are at 0.0025sec and 0.25% for period and damping, respectively

Conclusions

This paper discussed the use of portable wireless-based accelerograph units in vibration data collection of a full-scale shake table test building. The vibration data of the building under ambient conditions were recorded for 23 hours and 35 minutes and deployed in a variety of configurations. Utilizing one of the deployment configurations, these data were used to identify the modal parameters, including the vibration periods and the damping ratios of the building, using three output-only system identification techniques, namely, Power Spectral Density (PSD) analysis, Frequency Domain Decomposition (FDD), and Stochastic Subspace Identification (SSID). The analysis results showed that all three methods are robust in identifying the first three vibration periods of the building. However, comparing the identified damping ratios based on FDD and SSID techniques reveals that there are slight discrepancies between the estimated damping ratios. This is likely because damping ratios are very sensitive to noise and system identification model assumptions. In addition, monitoring the modal parameters for the 23 hours and 35 minutes data collection period showed that the building period decreases during the nighttime, potentially due to a minor increase in stiffness during colder hours, though this reduction in stiffness is not significant. Furthermore, it was concluded that the torsional mode of the building was only predictable when the wind speed was relatively larger, while during the calmer hours of the night, the torsional mode of the building was not identified. It is worth noting that conducting such system identification analysis is essential prior to the shake table test phase of such a large specimen, as such results provide information regarding the state of the building considering its as-built configuration, and eventually, these results ensure confidence in the results of the developed finite element models of the building.

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