Title: **Application of acceleration-based damage detection algorithms to experimental data from multi-story steel structures**

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ABSTRACT

This paper presents a recent shake table experiment on two three-story steel frame structures with controllable damage. The performance and accuracy of SnowFort, a wireless infrastructure monitoring system, were tested. By analyzing the data, we show that this new system achieves the same accuracy as the wired sensing units. In addition, a structural damage detection algorithm based on Continuous Wavelet Transform was validated based on the experimental data.

INTRODUCTION

Recently, there are several emerging evolutions on the structural health monitoring, specifically in wireless monitoring systems [1] and structural damage diagnosis methods [2]. However, these new systems and algorithms need to be validated and calibrated by laboratory experiments whereby damage is introduced in a systematic and controllable way. In this paper, we introduce a recent shake table test conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taipei, Taiwan. This experiment has three objectives: (1) validate the system performance and accuracy of SnowFort, an open source wireless infrastructural monitoring system [1]; (2) test an acceleration-based structural damage detection algorithm based on the Continuous Wavelet Transform [2] via experimental data; (3) detect non-linear behavior of a steel frame structure during different severe earthquakes. To satisfy these objectives, two identical structures with controllable damages were constructed and were tested with different levels of ground motions. In addition, different types of wireless and wired sensors, including three dimensional accelerometer and gyroscope, strain gages and linear variable differential transformers, were installed to collect measurements, which were used to validate the wireless monitoring system and the damage detection algorithm.

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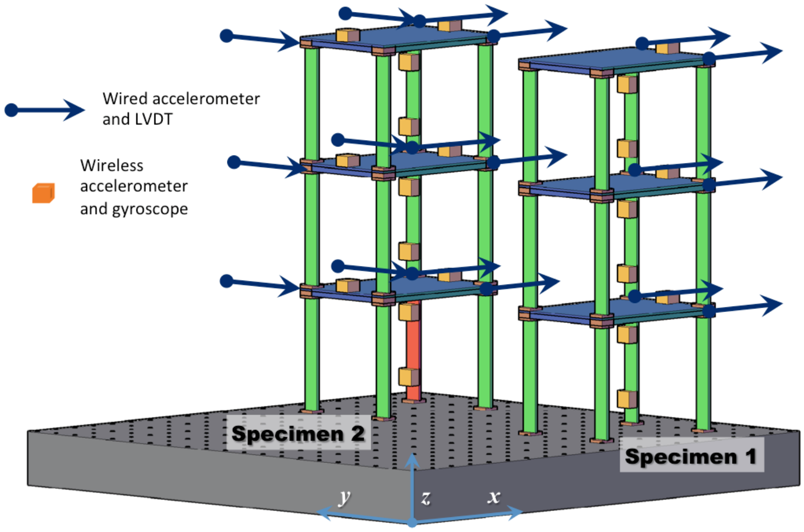


Figure 1: Two Structures and Sensor Locations used at the NCREE Experiment. The Weakened Column is in Red.

The rest of this paper is organized as follows. Firstly, We will describe the experiment with details on the specimens and the sensors. Then the performances of SnowFort will be analyzed via the Rotation Algorithm. Next, the Continuous Wavelet Transform-based algorithm will be demonstrated to be sensitive to the damage status and the wavelet coefficients can be used as the damage sensitive feature for structural damage detection. The conclusions from the study will be presented at last.

EXPERIMENT AND DATA ACQUISITION SYSTEM

Description of Experiment

This experiment was designed and performed at NCREE. Two identical three story single bay steel frames were constructed. Both structures have a inter story height of 1.1 m. Floor dimension at every story is 1.1 m × 1.5 m. The columns have rectangular cross-sections with a dimension of 0.15 m × 0.025 m × 1.06 m. On the weakened specimen, the NW column is replaced with a weakened column, which has a thickness of 0.015 m.

TABLE I: Summary of Ground Motions

Run Number	Amplitude (gal)	Run Number	Amplitude (gal)	Run Number	Amplitude (gal)
1	100	5	700	9	1300
2	250	6	850	10	1450
3	400	7	1000	11	850
4	550	8	1150	12	1000

These two structures were placed side by side on the same shake table. The

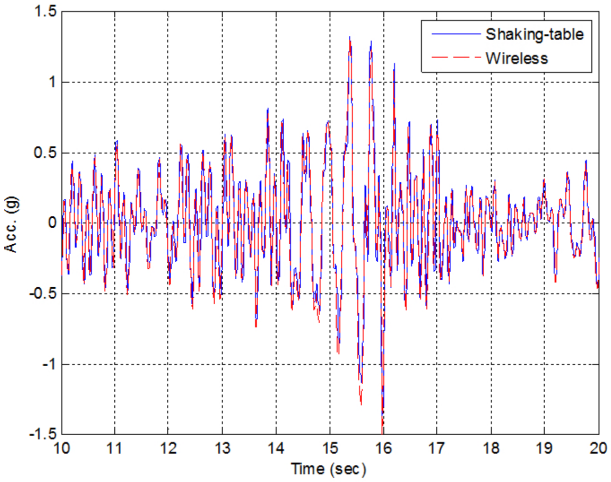


Figure 2: Comparsion of Wireless Sensor and Shake Table Recording in Run 4.

1999 Chi-Chi earthquake was applied in the X-direction with amplitudes progressively increasing from 100 to 1450 gal. White noise excitations with 50 gal amplitude were applied between strong motion runs. The strong motion amplitudes are summarized in Table. I. For the first 10 runs, a 500 kg mass block is placed on every story of both specimens. For the last two runs, an additional 500 kg mass block is added on the roof of each specimen.

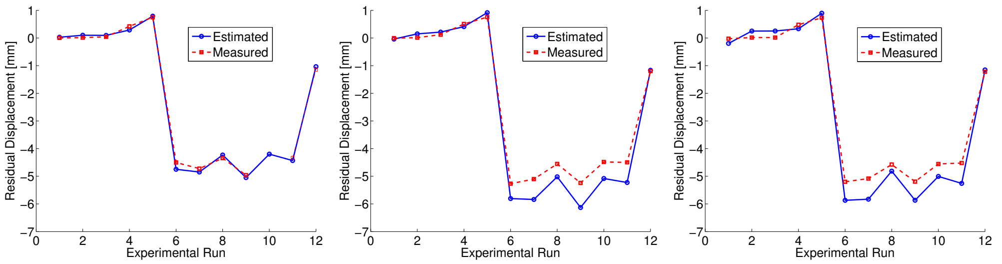
SnowFort Platform

SnowFort, an open source wireless sensor system designed for infrastructure monitoring is introduced in [1] recently. In this experiment, 21 wireless motes operating within the SnowFort system that are placed on the floors and columns, as shown in Fig. 1. Each mote is equipped with a three-axis accelerometer and a three-axis gyroscope. Data were collected at 52Hz sampling frequency and filtered with a 20Hz anti-aliasing filter. To justify the performance of these wireless sensors, the wired accelerometers, linear variable differential transformers (LVDTs), and strain gauges were installed in parallel. The sampling frequency of the wired sensors was 200Hz. In this paper, we use the measurements from both the wireless and wired sensors with random excitations and strong motions.

SYSTEM VALIDATION

In this section, we justify the performance of SnowFort system. Fig. 2 compares the acceleration measured by the wireless sensor and the recording of the shake table. We can observe that both signals overlap with each other perfectly.

To better understand the measurement quality of wireless sensors, we use the collected data to estimate the structure displacements and compare them with the true values measured by LVDTs. The displacements are estimated at different locations by using the measurements from wireless sensors. The "Rotation Algorithm" presented in [3] is employed.



(a) First Floor (b) Second Floor (c) Third Floor

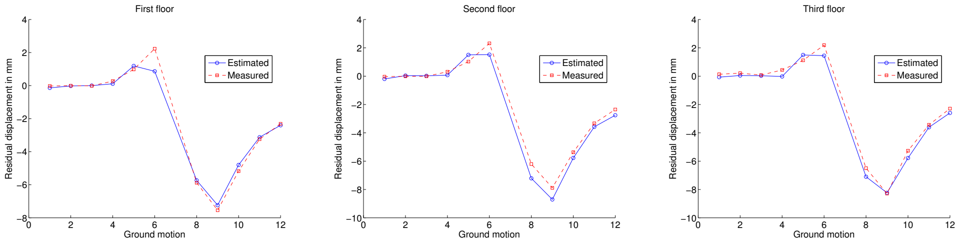
Figure 3: Estimated and Measured Residual Displacements for Specimen 1 in the Shaking Direction (X-axis).

The Rotation Algorithm uses the calculated residual rotations at several points along the height of the structure and fits a polynomial function to the rotations. That polynomial function is then integrated with respect to the structural height to provide a function that estimates the residual displacement along the height of the structure. An extended presentation of this algorithm can be found in [3]. The calculation of the rotation measurements can be embedded on the microprocessor of the sensing unit, thus requiring the transmission of only the final rotation values. While the estimation of the displacements requires the rotations from all sensors, the calculations involved can also be embedded in the microprocessor of the base station, which can then report the estimated displacements directly to the end user. Thus, the Rotation Algorithm provides a computationally efficient method to obtain reliable information on the residual displacements of a structure almost immediately after an extreme loading event.

To estimate the displacements, six sensors, two per floor, that measured accelerations in three dimensions were installed along the height of each of the specimens that are tested. The sensors were placed at the NW column and at $H/4$ away from the top and bottom of each story, where $H = 1.1$ m is the story height. All sensors were utilized and a fourth order polynomial was used to estimate the displacements. The rotations at the sensor locations were calculated using 500 points (approximately 10 seconds) of ambient vibration before and after each ground motion. For the full strength specimen, which was expected to deform in one plane, the two-dimensional version of the algorithm was applied.

Fig. 3 shows a comparison between the estimated displacements and direct displacement measurements obtained through LVDTs. It should be noted that while the rotations were calculated at the locations of the sensors (two per story), the displacements reported in Fig. 3 refer to the floor heights, where the LVDTs were installed. This highlights the capability of the rotation algorithm to estimate the displacement at any point along the height of a structure as well as the accuracy of the wireless sensors. From the figure, we can observe that the maximum gap between the estimate and true displacement is less than 1 mm.

In the case of the weakened specimen, where torsion and out-of-plane movement were expected, the three-dimensional version of the algorithm is applied. The estimated and measured displacements for the shaking direction is shown



(a) First Floor (b) Second Floor (c) Third Floor

Figure 4: Estimated and Measured Residual Displacements for Specimen 2 in the Shaking Direction (X-axis).

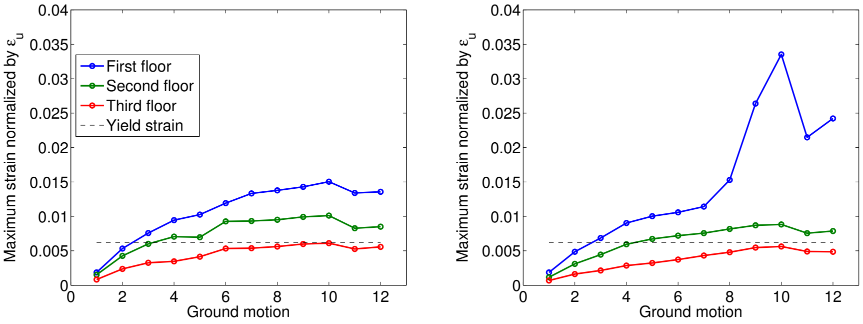
in Fig. 4. Run 7 is missing due to an unexpected power outage of the wireless base station during the test. It can be observed that the rotation algorithm can provide very good estimates of the residual displacements for both specimens.

In summary, the perfect overlapping of the measured acceleration and the shaking table signal indicates that the wireless sensors have high accuracy. Also, by comparing of the displacement estimation with the LVDT measurements, we can conclude that the wireless sensing unit operating within the SnowFort system can provide robust measurements. Compared with the wired sensors, the wireless sensors have many advantages, such as small size, low power consumption and the ease of installation and maintenance. This proof-of-concept experiment results will allow us to use wireless sensing unit alone in the future.

DAMAGE DETECTION

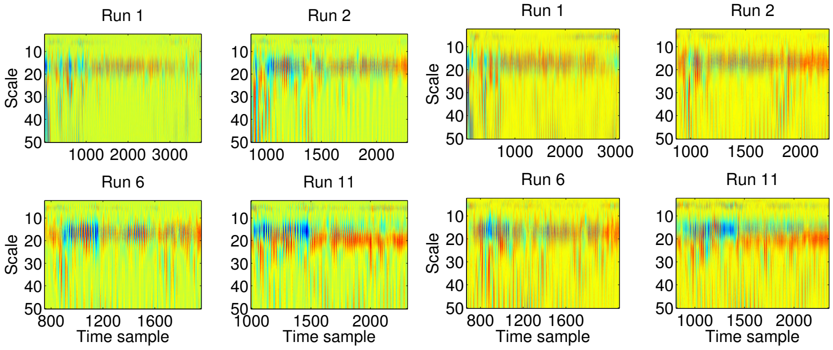
In this section, we analyze the performance of the Continuous Wavelet Transform (CWT) based damage diagnosis algorithm. The Wavelet Gaussian Process algorithm uses the CWT of the structural response to the strong motion in conjunction with Gaussian Process Theory. The outputs of this damage detection algorithm are the residual terms, the amplitude, the stretch and the shift parameters. Each residual term corresponds to one time sample and their dimensions correspond to the scales at where the CWT is evaluated. The distributions of the model parameters over an entire recording have been found to depend on the damage state of the structure, indicating a capability for detecting the presence of damage over an entire record. The Gaussian terms extracted from the statistical model also correlate with the damage state of the structure, indicating a potential for temporal localization and, thus, quantification of the extent of damage. The details of the algorithm formulation and a demonstration of its capabilities can be found in [2, 4].

The Wavelet Gaussian Process algorithm is applied to the acceleration measurements obtained from wired sensors, placed both on the columns and on the floors of the structures. In order to evaluate the results of the damage detection algorithm, the presence or absence of damage is determined through the data obtained from strain gauges installed on the columns of the frames. Fig. 5 shows the maximum strain at each floor for each ground motion. The strains reported have been normalized by the ultimate strain (ϵ_u) of the steel used to highlight the fact that, while the structure did behave non-linearly, the overall level of damage sustained was very low. The dashed line is the threshold of damage.



(a) Full Strength Specimen (b) Weakened Specimen

Figure 5: Maximum Strain at Each Floor, Normalized by the Steel's Ultimate Strain.

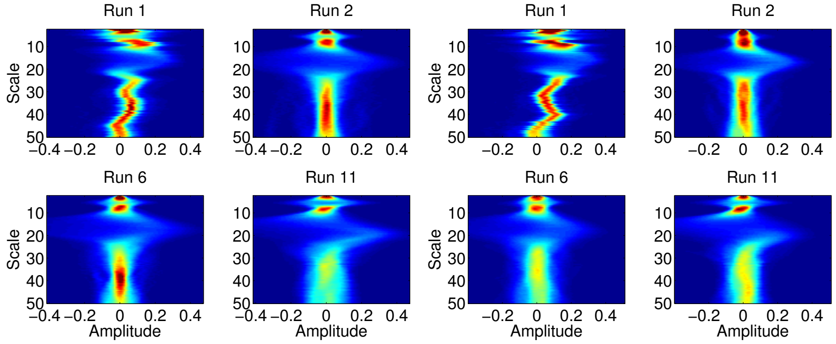


(a) Full Strength Specimen (b) Weakened Specimen

Figure 6: Gaussian Process Residuals for the Two Specimens and Selected Experimental Runs.

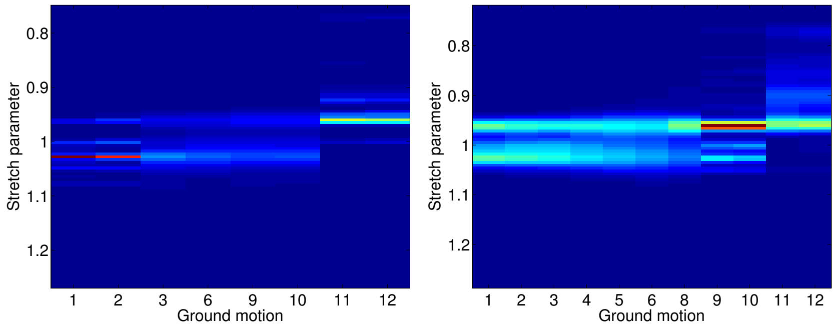
The residual terms resulting from the Wavelet Gaussian Process algorithm are plotted, for selected runs, in Fig. 6a and in Fig. 6b. The sensor that corresponds to the full strength specimen was placed on the second floor of the structure and the sensor that corresponds to the weakened specimen was placed on the NW column of the second floor of the structure. While there is no clear indication of damage, Run 6, during which damage occurred, exhibits an extended interval of outliers which can be observed as blue regions between scales 15 and 25. Furthermore, the residuals in Run 11 appear significantly different to the baseline for both specimens. This is due to the fact that there was an additional mass on the roof of both structures for Runs 11 and 12, a change in structural properties is detected.

Fig. 7 shows Kernel Density Estimates (KDE) for the residual terms and experimental runs plotted in Fig. 6. According to the statistical model, the residual terms should follow the same distribution while the structure remains undamaged and that distribution changes with the progression of damage. In this case, the distribution of the residuals appears to change significantly between



(a) Full Strength Specimen (b) Weakened Specimen

Figure 7: KDE for the Residual Terms at Each Scale.



(a) Full Strength Specimen (b) Weakened Specimen

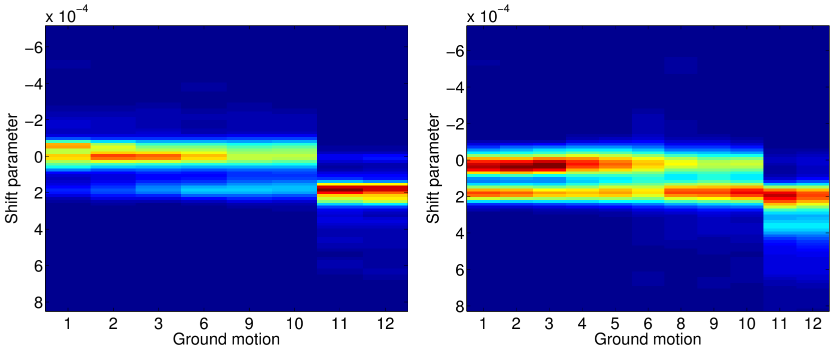
Figure 8: KDE for the stretch parameter at each experimental run.

the two undamaged runs (Runs 1 and 2). However, there is also a visible change in distribution as damage progresses.

The change in distribution is more easily observed in the distributions of the stretch and shift parameters of the model. Fig. 8 and Fig. 9 show KDE for the stretch and shift parameters, respectively, for all experimental runs. For the model parameters, there is visible similarity in the distributions in the two undamaged runs and a gradual divergence as damage progresses. Furthermore, there is a clear jump in the last two runs which, as mentioned previously, correspond to the specimens with added mass.

CONCLUDING REMARKS

This paper presents the results from the analysis of data obtained from a recent shake table test on the steel frame structure with multiple types of sensors installed. We analyze and discuss the performance and the accuracy of a new wireless monitoring system, SnowFort, via the Rotation Algorithm. The gaps between the displacements estimated by utilizing the wireless sensors and measurements of LVDT are within 1mm, which indicates that SnowFort can achieve the same accuracy as the wired system. Other validation results of SnowFort will be discussed in the extended paper. In addition, we use the



(a) Full Strength Specimen (b) Weakened Specimen

Figure 9: KDE for the shift parameter at each experimental run.

experimental data to validate that the wavelet coefficients are sensitive to the statue of damage and loading conditions. The results presented in this paper are encouraging and show that this experimental data set is promising for the validation and calibration of other damage detection algorithms.

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