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COMPARATIVE STUDY OF DISPLACEMENT MEASUREMENTS FROM SHAKING TESTS OF A FULL-SCALE 10-STORY BUILDING

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Abstract: *Seismic response monitoring or structural health monitoring, in general, relies on acceleration measurements from a vibration monitoring system installed on the structure. Structural displacements, or more precisely, interstory drifts, are important for the integrity of typical building-type structures. Furthermore, interstory drift is also an important metric to assess the damage and ductility characteristics of a building subjected to large earthquakes. This critical response parameter is evaluated by using double integration of acceleration data with appropriate detrending and filtering techniques. The displacements calculated in such a way are easy to obtain since they make use of unobtrusive and widely available strong motion instrumentation. However, the accuracy of these displacements depends on the type of sensors and the signal processing techniques, which may be subjective. This study focuses on the comparison of multiple displacement measurements obtained through the numerical integration of multiple accelerometers, direct contact displacement transducers between the test structure and a reference frame, and non-contact differential GNSS-based techniques. Data is collected on the shake table testing of a large-scale 10-story mass timber rocking wall building, incorporating uplift friction dampers at the base of the rocking wall in combination with U-shaped flexural plates, at the world's largest outdoor earthquake simulator at the University of California San Diego (UCSD). These tests were conducted as part of a larger shake table test program led by the NHERI TallWood Team investigating seismically resilient tall mass timber buildings. The displacement responses of the building under different types of seismic loadings are presented to gauge the effectiveness of accelerometers with respect to benchmark direct contact displacement techniques. Non-contact differential GNSS-based technique is compared and validated using the best available benchmark displacement response.*

1 Background

Accurate displacement measurements are critical for the integrity of the buildings since these displacements are used in interstory drift ratio calculations i.e., relative translation between two floors normalized by floor height. This important structural parameter is one of the key indicators of seismic performance of the buildings. Building codes and design guidelines have identified limits on this parameter based on the historical data from instrumented buildings and experimental evaluation in laboratories. It is used as the main engineering demand parameter to conduct fragility analysis as structural damage and some non-structural damage correlates with this parameter as highlighted by Algan (1982). Owing to the importance of this parameter, it is imperative that structural displacements be accurately measured.

In contemporary world, many real-time systems record earthquake response of the building and present the critical information to the building managers/owners in terms of floor drifts and floor accelerations, thus directly providing an indication of whether the building underwent damage or not. Due to ease of installation and operability, nearly all of these systems employ accelerometers, which record acceleration response. The displacement response is usually obtained by double integration of acceleration with filtering process which is somewhat subjective in nature. A critical assessment of this approach is made by Skolnik and Wallace (2010). Their study indicates that an acceptable level of accuracy in displacements can be achieved with this method in the linear range. However, if the building response enters non-linear range, the errors in displacement estimates increase due to inability of the system to catch permanent displacements arising mainly from filtering of data. Displacement transducers require contact between structure and a rigid reference frame, while non-contact methods such as optical based systems are also largely impractical for commercial application. Therefore, the most convenient method is to obtain displacements through double integration of acceleration data. Nevertheless, not all accelerometers can produce accurate displacement response in the linear range.

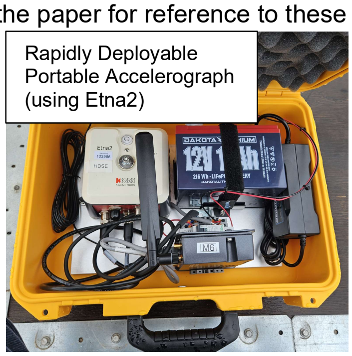
In order to test the displacement response of different types of accelerometers under earthquake loading, NHERI TallWood project provided a unique opportunity to evaluate these results where different type of data acquisition systems are deployed on a full-scale 10 story mass timber building. The building is highly instrumented with different types of accelerometers, such as MEMS, Force-Balanced Accelerometers, Variable Capacitance Accelerometers. A subset of these accelerometers are used to compare their displacement response with reference contact based displacement string potentiometers. The best displacement response producing accelerometer is employed to further compare and validate the results of non-contact GPS system, which measures position at considerably lower sample rate. The results reported in this paper are part of a payload study (Dowden and Tatar 2024) conducted after the NHERI TallWood project team completed their tests.

2 Experimentation Protocol

The experimental protocol involves the world's largest outdoor shake table, which is 40 ft x 25 ft in size, and possesses 20 MN (4500 kips) of vertical payload capacity. The table has 6 degrees-of-freedom and can accommodate ±889 mm (±35 in), ±381 mm (±15 in), ±127 mm (±5 in) of displacements in X, Y, and Z directions, respectively. The table can produce frequencies between 0-33 Hz, which are of interest for structural engineering community. The test building is unique in the sense that it is the tallest full-scale building ever tested on a shake table. This mass timber building is equipped with rocking wall based lateral load resisting system incorporating uplift friction dampers at the base of these rocking walls in combination with U-shaped flexural plates attached to boundary columns at the floor/roof levels. This 10-story building is highly instrumented with various types of data acquisition sensors and was subjected to an extensive set of earthquake/ground motions. However, only a small subset of these instruments and ground motions are used in this study. The details about the building, sensors, and the earthquake ground motions employed in this study are presented in the following subsections.

2.1 Shake Table and Instrumentation

The instrumentation used in this study included micro-electromechanical system (MEMS) based accelerometers, Kinemetrics' Force Balanced Accelerometers (FBA) based accelerograph, String Potentiometers, GNSS/GPS system. It is noted that FBA-based accelerographs are housed in portable, rapidly deployable boxes. The portable accelerograph is equipped with its own power, GPS antenna (for timing), and cell modem, all within the box, for uninterrupted (near) real-time transfer of data to a remote computer/cloud environment. As an example, Figure 1a shows a depiction of the portable accelerograph, and Figure 1b shows GPS system (for position measurement). Some salient features of the data acquisition system used in the study are listed in Table 1. For simplicity, MEMS, Etna2, String Pot, and GPS naming convention will be used throughout the rest of the paper for reference to these systems.



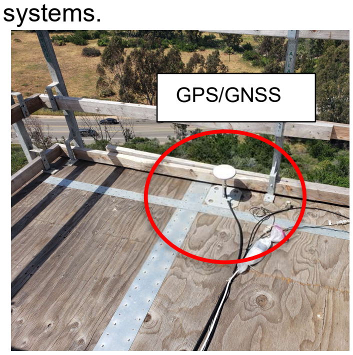


Figure 1. Instrumentation a) Kinemetrics Rapidly Deployable Portable Accelerograph b) GPS/GNSS

Table 1. Instrumentation type and characteristics

Instrument type	Full Scale Range	Bandwidth (Hz)	Cross-Sensitivity	*Sampling Rate (Samples per Second)
MEMS Accelerometers	10g	DC – 350 Hz	<3%	256
Etna2 Triaxial EpiSensor FBA based Accelerograph	4g	DC – 200 Hz	<1% including misalignment	200
String Potentiometers (Displacement measurement)	-	-	-	256
GNSS/GPS (Position measurement)	-	-	-	100
Shake Table (Controller displacement)	-	-	-	512

*Sampling rate only indicates frequency at which data is sampled and does not necessarily mean sampling capability of the instrument

2.2 Building Floor Plan and Instrumentation Locations

The building is instrumented with MEMS and Etna2s near the Center of Mass (CM) of the building at Floor 1 to Floor 4, while string pots are installed on the southeast and southwest sides to measure displacement in Y-direction on Floor 2, 3, and 4 and near CM to measure displacement in X-direction for Foor 2 and 3. It is noted that Floor 1 is the ground floor on the shake table. As mentioned in section 2.1, while the building is highly instrumented with various sensors, only a subset of instruments are shown which are relevant to this study. Figure 2a presents a typical floor plan for Floor 1 to 4, while GPS and Etna2 locations on the roof are shown in Figure 2b.

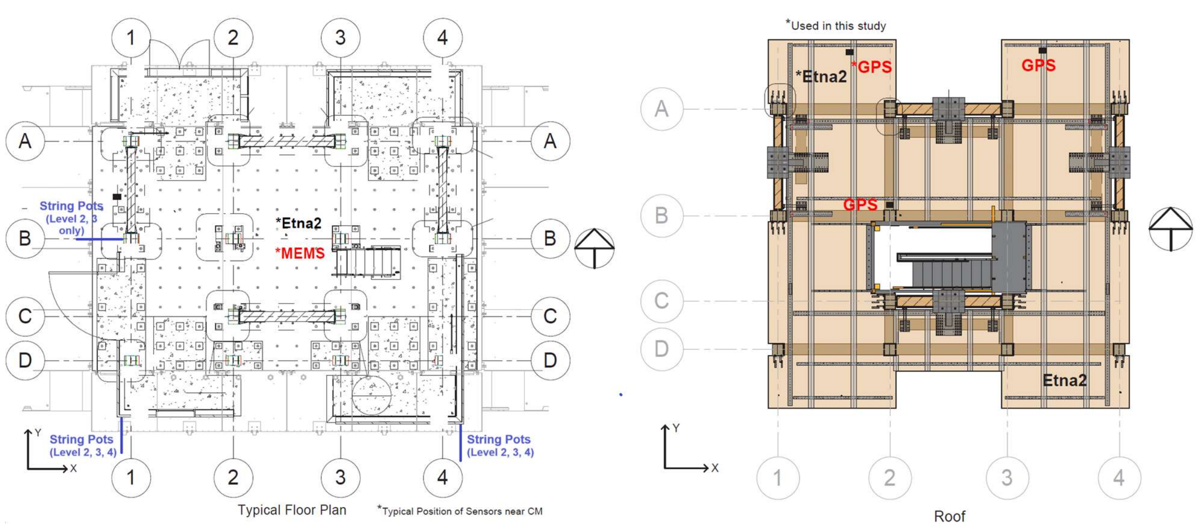


Figure 2. Floor plan a) Typical b) Roof (Adopted from NHERI Tallwood Layout)

2.3 Earthquake/Ground Motions

The ground motions used in this study include records from the 1989 Loma Prieta earthquake scaled to risk targeted Maximum considered MCE_R level return period (2475 years), the 1980 Victoria (Mexico) earthquake scaled to a return period of 975 years, and the 1999 Chi-Chi earthquake scaled to a return period of 475 years (Design Basis Earthquake). Loma Prieta ground motion is applied in Y-direction with target input PGA of 0.7587g. Victoria ground motion is used as a bi-directional input (YZ) with target PGAs of 0.505g (X), 0.188g (Z), while Chi-Chi ground motion is used to excite all three directions (XYZ) with target PGAs of 0.4671g (X), 0.2614g (Y), 0.2370g (Z). A detailed presentation on the ground motion scaling and development of ground motions used in these tests can be found at Wichman et al. 2022.

3 Methodology and Analysis

3.1 Assessment of Unfiltered Acceleration Data

The acceleration data obtained at the Floor 1 (ground floor) is analyzed to assess the differences between data collected from MEMS and Etna2. A baseline correction is made to both the records by subtracting their respective means (averages), however, no frequency filtering is employed. Unfiltered acceleration time-history is presented in Figure 3. It is not easier to analyze the signals in time-domian; therefore, the Fast Fourier Transformation (FFT) is shown in Figure 4. It is evident from Figure 4 that the FFT of MEMS is noisier and shows higher amplitudes at most of the frequencies compared to Etna2. An additional assessment is done by constructing acceleration response spectra at various damping values ($\zeta = 0\%, 2\%, 5\%$) as a percentage of critical damping. It can be seen from Figure 5 that undamped spectra of MEMS and Etna2 show significant differences (e.g., at T=0.15s, spectral acceleration differs by 1g). Nevertheless, this difference in values starts to diminish as damping is added to the response, and the spectra become smoother due to the damping effect.

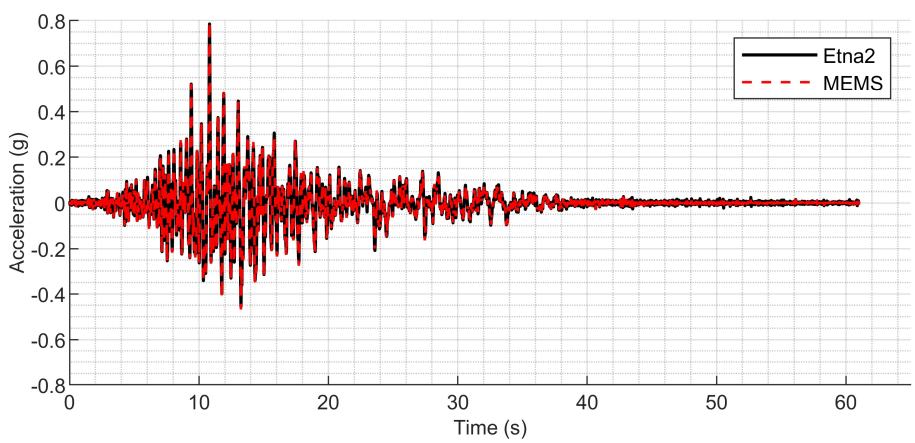


Figure 3. Unfiltered acceleration time-history

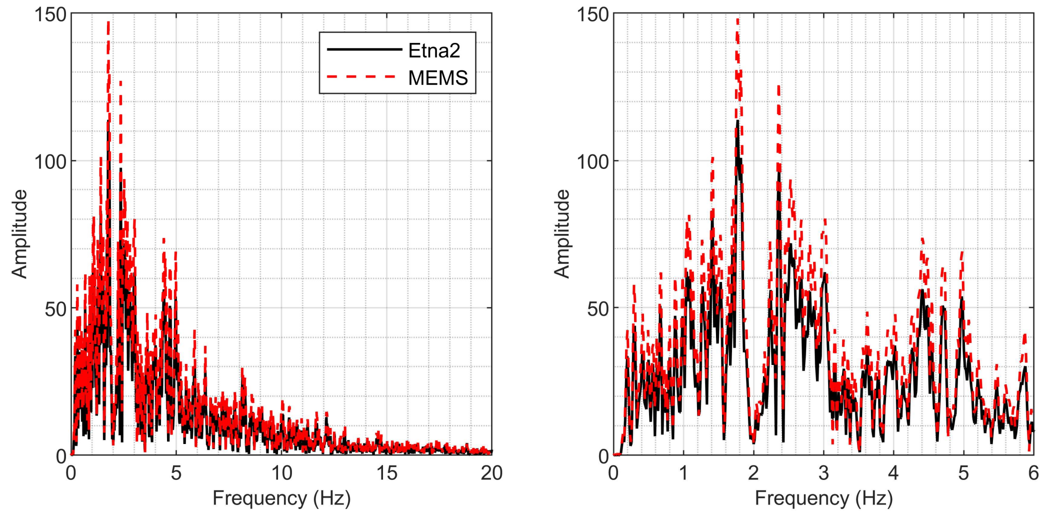


Figure 4. Frequency domain analysis a) FFT b) FFT zoomed in to show differences at lower frequencies

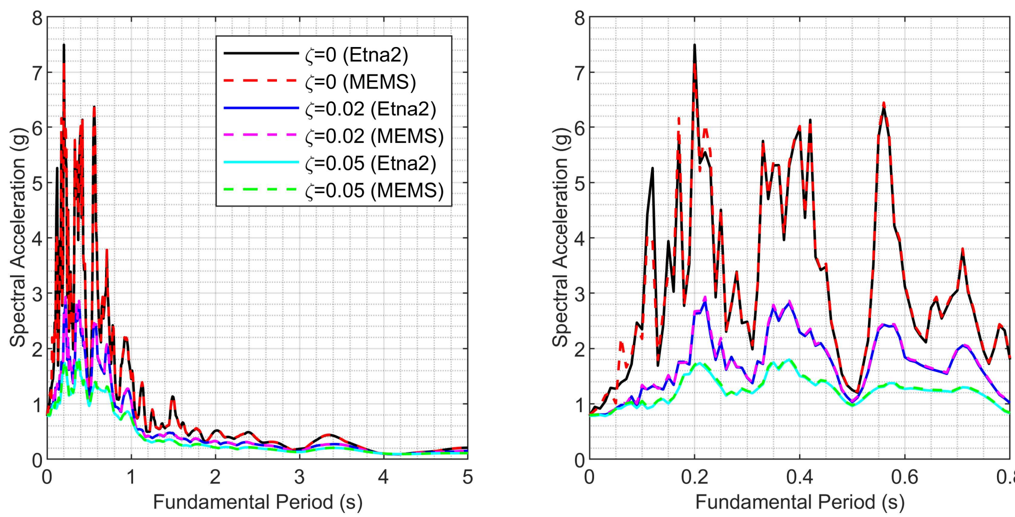


Figure 5. Ground Motion a) Response Spectra b) Response Spectra zoomed in to show differences

3.2 Frequency Filtering and Displacement Comparison

If necessary, a Hampel outlier is applied to remove any spikes from unfiltered data by considering a large sample window and very large standard deviation. The unfiltered acceleration data from MEMS and Etna2 are converted into displacements using double integration of data with appropriate detrending and frequency filtering. Butterworth filter is used for frequency filtering, with a high pass frequency as a variable, while the low pass frequency is fixed to 50 Hz. Since lower frequencies are of interest to this study involving displacement comparisons, a high pass frequency of 0.01 Hz is used as a starting point for calculating displacements. The high pass frequency is then increased in small increments and corresponding displacement time-histories are obtained for both MEMS and Etna2s. It is important to highlight that Etna2 data is manually synched to MEMS and string pot data since it has its own independent timing and recorded data continuously instead of triggering with other instruments. A typical cycle depicting displacement calculation is shown in Figure 6. The displacements from MEMS and Etna2 are compared with benchmark displacements of string pots (at Floor 2, 3, 4) and shake table displacement (at Floor 1). Only baseline correction is applied to the benchmark displacements, frequency filtering is not implemented. The error with respect to benchmark displacement time-histories is calculated in terms of Root Mean Squared Error (RMSE). Once lowest RMSE is achieved for MEMS and Etna2s and RMSE starts increasing again, the high pass frequency increments and calculation cycles are stopped since further filtering is unnecessary. RMSE approach helps to identify the best high pass filter for both MEMS and Etna2s, respectively. The analysis done under three different ground motions is presented in the following subsections.

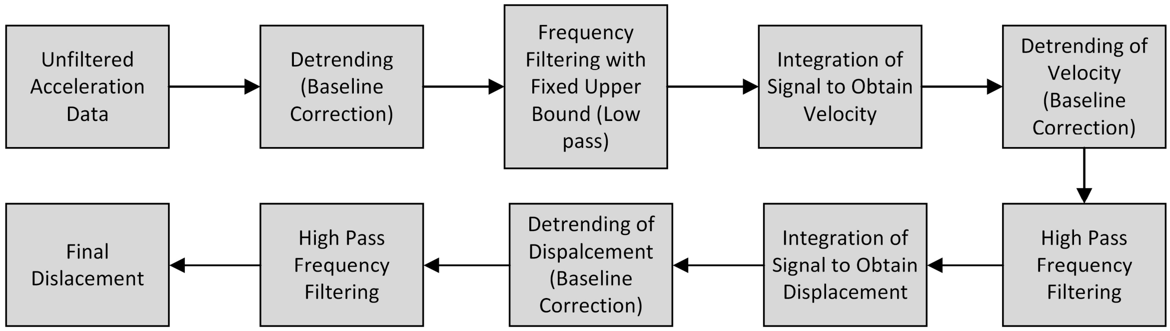


Figure 6. Flow chart for displacement calculation

1989 Loma Prieta Earthquake Record

Loma Prieta record is only applied in Y-direction of the building, therefore, the displacements obtained in Y-direction are compared. It is noted that displacements are compared for only first 4 Floors since benchmark string pots and/or controller displacement are only available for those floors. Comparison of displacements with a high pass frequency of 0.01 Hz is shown in Figure 7a. It is evident that MEMS yield large errors for all floors, while Etna2 displacements are much closer to the benchmark responses of the shake table controller and string pots. On average, for all floors, a high pass frequency of 0.06 Hz yields least RMSE for Etna2, while a high pass frequency of 0.10 Hz yields best results or least RMSE for MEMS. The best results for MEMS are shown in Figure 7b. Even in the best case scenario for MEMS, Etna results are much closer to the benchmark displacement. This is particularly appreciable for Floor 1, where MEMS displacement is noticeably different around 10s. Figure 8 presents the results of RMSE at different high pass frequencies. The legend shows RMSE considering benchmark shake table displacement for Floor 1 in Figure 8a, while legend in Figure 8b, 8c, 8d show RMSE with respect to SE and SW benchmark string pot displacements. The results show the accuracy of Etna2 displacements with near zero RMSE errors for all four floors although Etna2 response is manually time synched with the benchmark data.

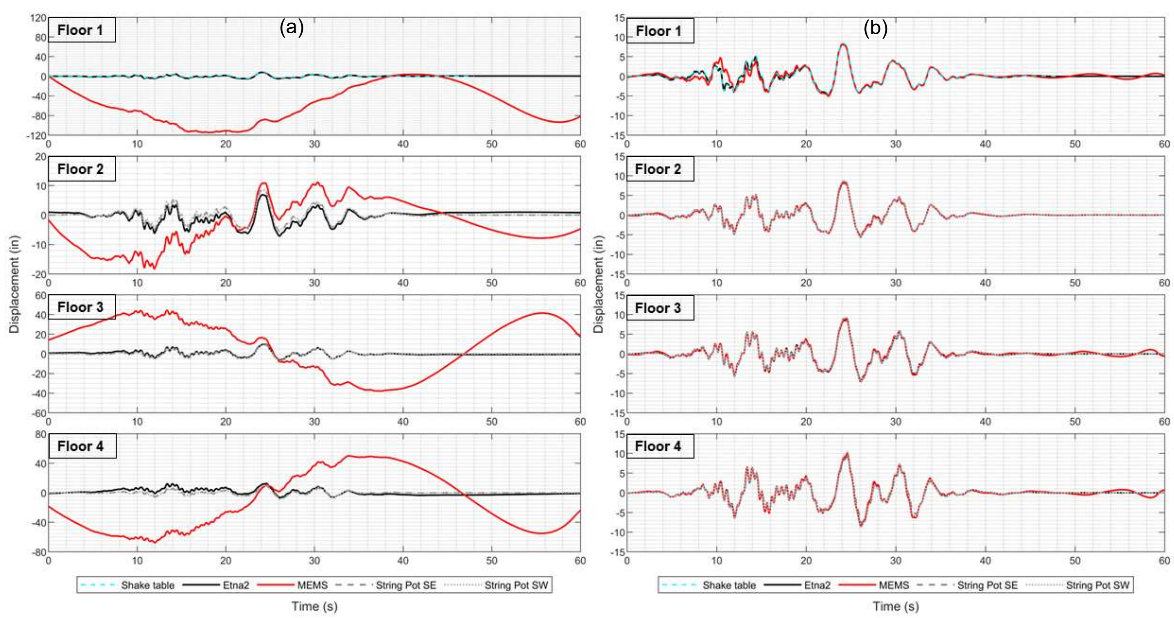


*Figure 7. Loma Prieta: Displacement comparison with a high pass frequency a) 0.01 Hz (*Y-axis is not fixed) b) 0.10 Hz*

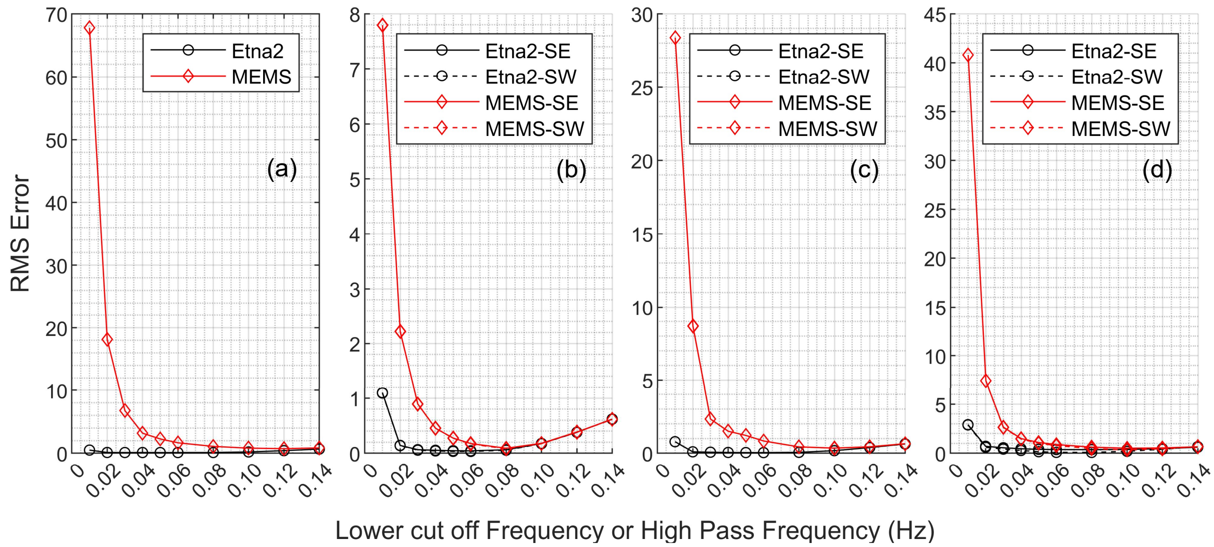


Figure 8. Loma Prieta: RMSE with different high pass frequencies a) Floor 1 b) Floor 2 c) Floor 3 d) Floor 4

1980 Victoria Earthquake Record

Though this record is used to excite both Y and Z directions, results are presented only for Y-direction since no benchmark displacement is available in Z-direction. In this case, Etna2 produces adequately accurate results at a high pass frequency of 0.04 Hz as shown in Figure 9a, where MEMS show considerably large errors. The base case scenario for MEMS is obtained at a high pass frequency of 0.22 Hz, which is more than 5 times the best case high pass frequency of Etna2 (Figure 9b). Even in this case, there is appreciably large error between MEMS and string pot displacements throughout the strong motion. Due to elimination of lower frequencies, the peak response around 6 - 6.5 s is underestimated by more than an inch. Figure 10 and 11 present these results in terms of interstory drifts (i.e., relative translations between floors) with high pass frequencies of 0.04 Hz and 0.22 Hz. At 0.04 Hz, the Etna2 drifts matches the drifts from string pots (especially string pot SW), while MEMS overpredicts drifts by more than 7 inches during strong ground motion. At 0.22 Hz, which is the best case scenario for MEMS, they still overpredicts drifts by more than 1 in. Near zero RMSE in displacement response is obtained for Etna2, while large errors for MEMS are evident in Figure 12. These large errors in MEMS during bi-directional excitation may be attributed to its high cross-sensitivity compared to Etna2, which results in more noisy data in the direction of interest.

1999 Chi-Chi Earthquake Record

Chi-Chi earthquake record is applied as tridirectional (XYZ) input to the building. Both X and Y directions are analyzed in this case, while Z direction is not considered due to lack of reference/benchmark displacement. However, in this case, only Floor 3 is studied for brevity. The benchmark displacement in X-direction is a string pot at the Center of Mass (CM). The best-case scenario for Etna2 is shown in Figure 13a where the high pass frequency is 0.05 Hz. Etna2 displacements are reasonably accurate in both X and Y directions under this tridirectional excitation. On the other hand, the best-case MEMS displacements (Figure 13b), which are obtained at a high pass frequency of 0.12 Hz, underestimates the peak responses by more than inch between 10-25 s of the strong motion due to removal of low frequencies. At this high pass frequency, Etna2 shows similar response to MEMS during strong ground motion, however, Etna2 matches the string pot response of zero displacement (rest/initial position) following the strong ground motion, which is not the case for MEMS. Again, RMSE errors in both X and Y direction are near zero for Etna2, as shown in Figure 14.

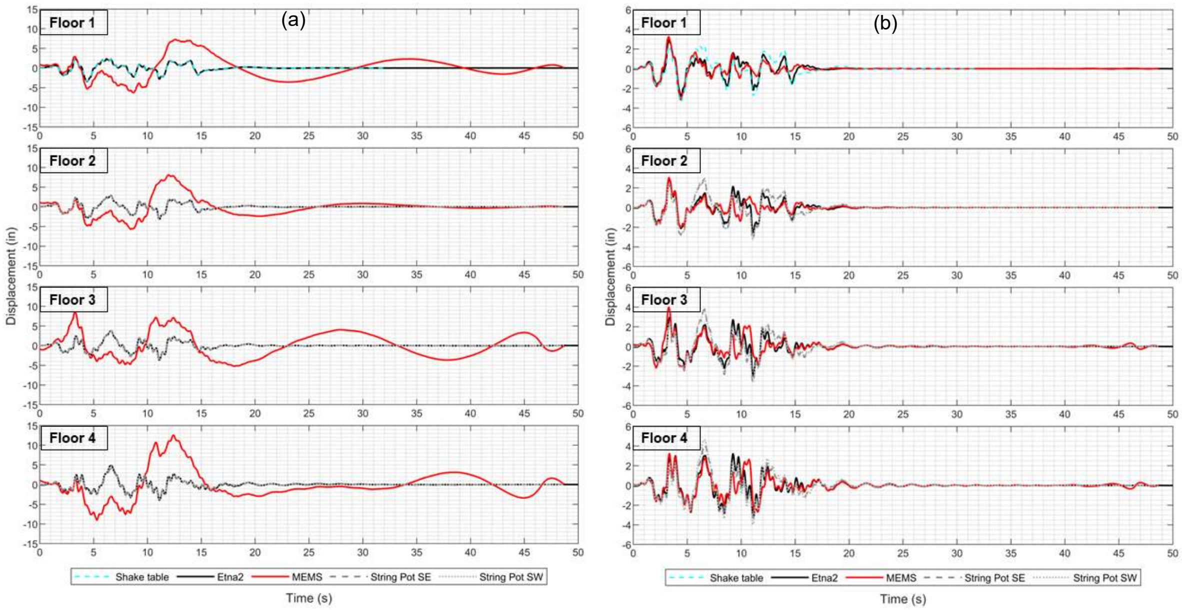


Figure 9. Victoria: Displacement comparison with a high pass frequency a) 0.04 Hz b) 0.22 Hz

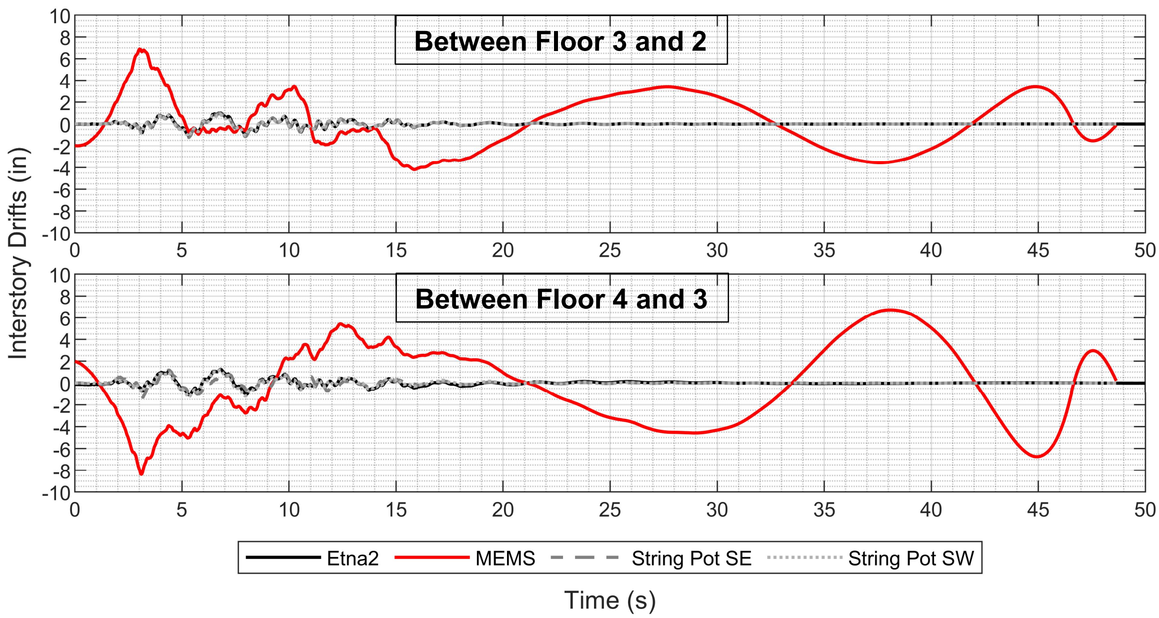


Figure 10. Victoria: Interstory drifts with a high pass frequency of 0.04 Hz

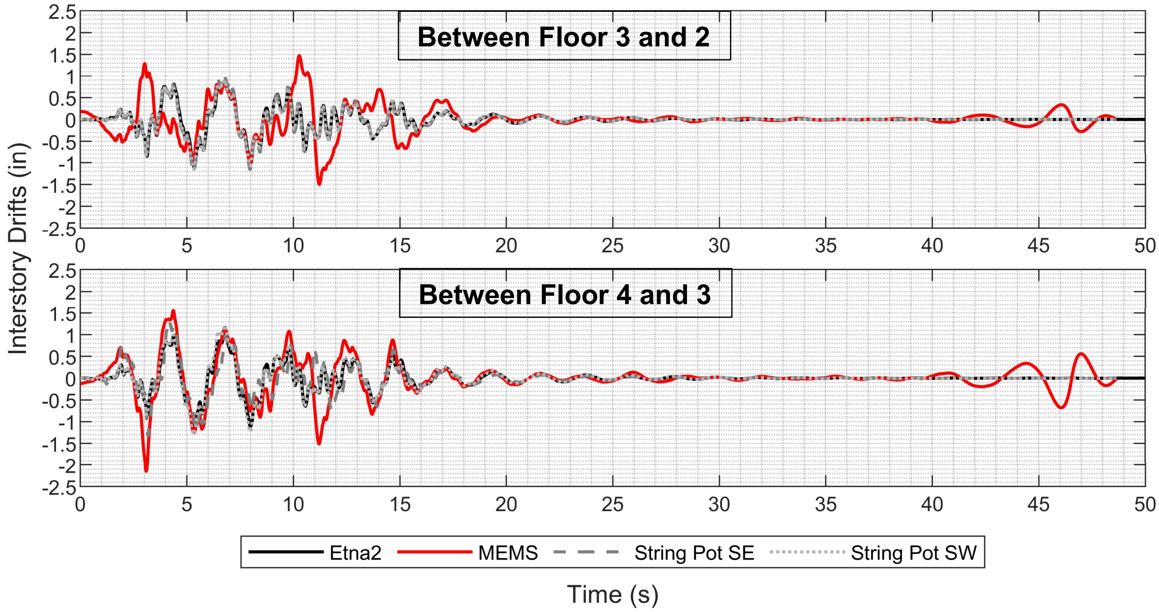


Figure 11. Victoria: Interstory drifts with a high pass frequency of 0.22 Hz

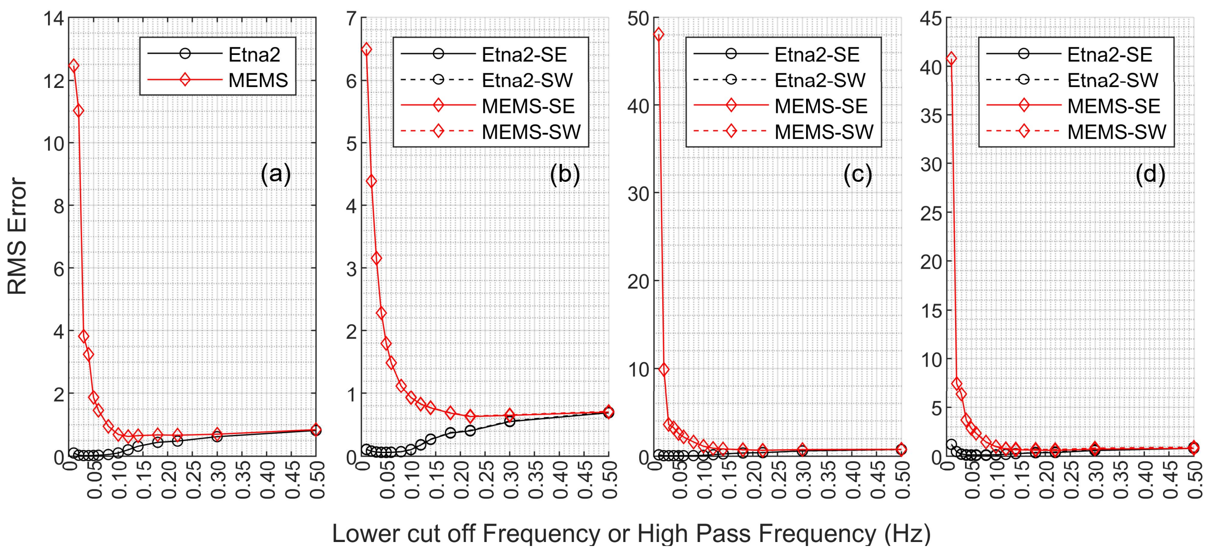


Figure 12. Victoria: RMSE with different high pass frequencies a) Floor 1 b) Floor 2 c) Floor 3 d) Floor 4

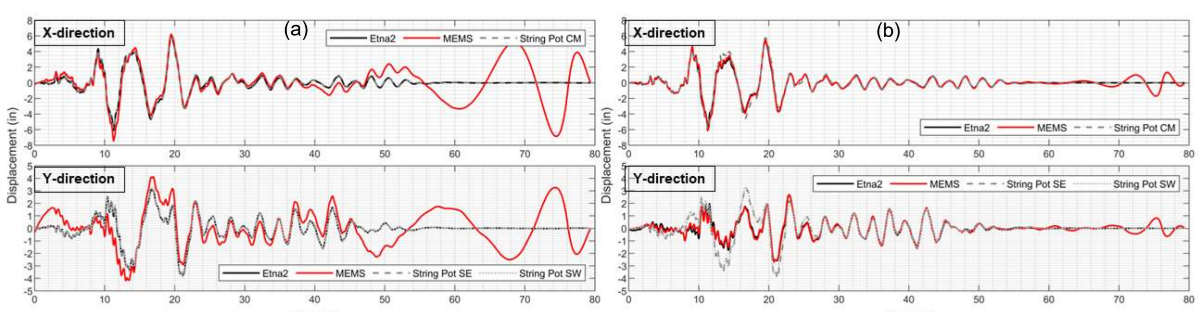


Figure 13. Chi-Chi: Displacement comparison for Floor 3 with a high pass frequency a) 0.05 Hz b) 0.12 Hz

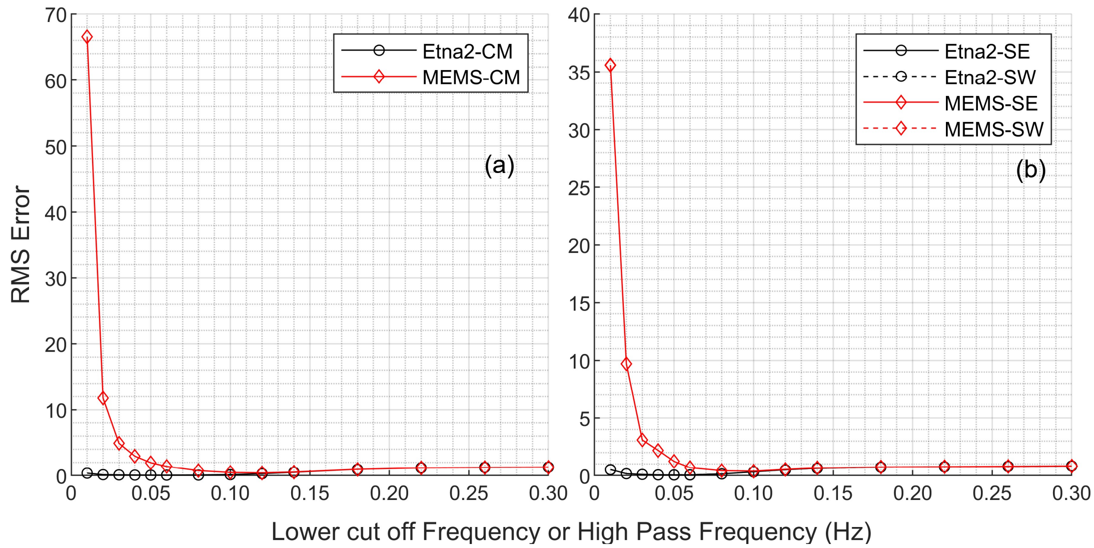


Figure 14. Chi-Chi: RMSE for Floor 3 with different high pass frequencies a) X-direction b) Y-direction

Summary of Comparative Results

The summary of minimum RMSE errors and the respective high pass frequencies that yield minimum error for Etna2 and MEMS are presented in Table 2 for all three ground motions. The minimum RMSE error for MEMS varies from 2.3 to nearly 25 times of Etna2s RMSE. These huge errors could lead to inaccurate interstory drifts, which is a vital structural response parameter. On average, accurate results can be obtained from Etna2 with a high pass frequency of 0.05 Hz. Owing to the accuracy of Etna2 in terms of displacement response, it is used to compare and validate GPS response in the section 3.3.

Table 2. Minimum RMS Error Analysis

Earthquake Record	**Floor**	**Direction Analyzed**	**Etna2** High Pass Frequency (Hz)	**Etna2** Minimum RMSE Error	**MEMS** High Pass Frequency (Hz)	**MEMS** Minimum RMSE Error
Loma Prieta	1st	Y	0.06	0.1180	0.12	0.7286
(Unidirectional – Y)	2nd	Y	0.06	0.0340	0.08	0.0814
	3rd	Y	0.06	0.0467	0.10	0.3479
	4th	Y	0.08	0.0880	0.10	0.3475
Victoria, Mexico	1st	Y	0.03	0.0260	0.12	0.6310
	2nd	Y	0.05	0.0625	0.22	0.6310
(Bidirectional – YZ)	3rd	Y	0.04	0.0768	0.22	0.6830
	4th	Y	0.06	0.0998	0.22	0.6041
Chi-Chi, Taiwan	3rd	X	0.06	0.0621	0.12	0.4068
(Tridirectional–YZ)	3rd	Y	0.05	0.0486	0.10	0.3813

3.3 Comparison and Validation of GPS Response

The GPS data obtained from the roof of the building is compared with the benchmark roof displacement response from Etna2. For this purpose, the response data from tri-directional Chi-Chi earthquake record is used. Reference Etna2 roof displacements in X and Y directions are evaluated by employing high pass frequency of 0.05 Hz. GPS station near the northwestern corner of the building is used since it is closest to the Etna2 on northwestern corner on the roof. Figure 15a and 15b show time history comparison in X and Y directions, respectively. Although minor variations exist at few points, it is obvious that the displacements from GPS are fairly accurate when compared with Etna2 displacements. These X and Y displacements are plotted against each other in Figure 15c and 15d to compare the two-dimensional roof response throughout the tri-directional ground motion. The peak response between 18 to 24s of time-history is highlighted with thicker lines. It can be concluded that, despite low sampling rate, GPS response can be employed for displacement calculations where other means of measuring displacements, such as string pots, are not available.

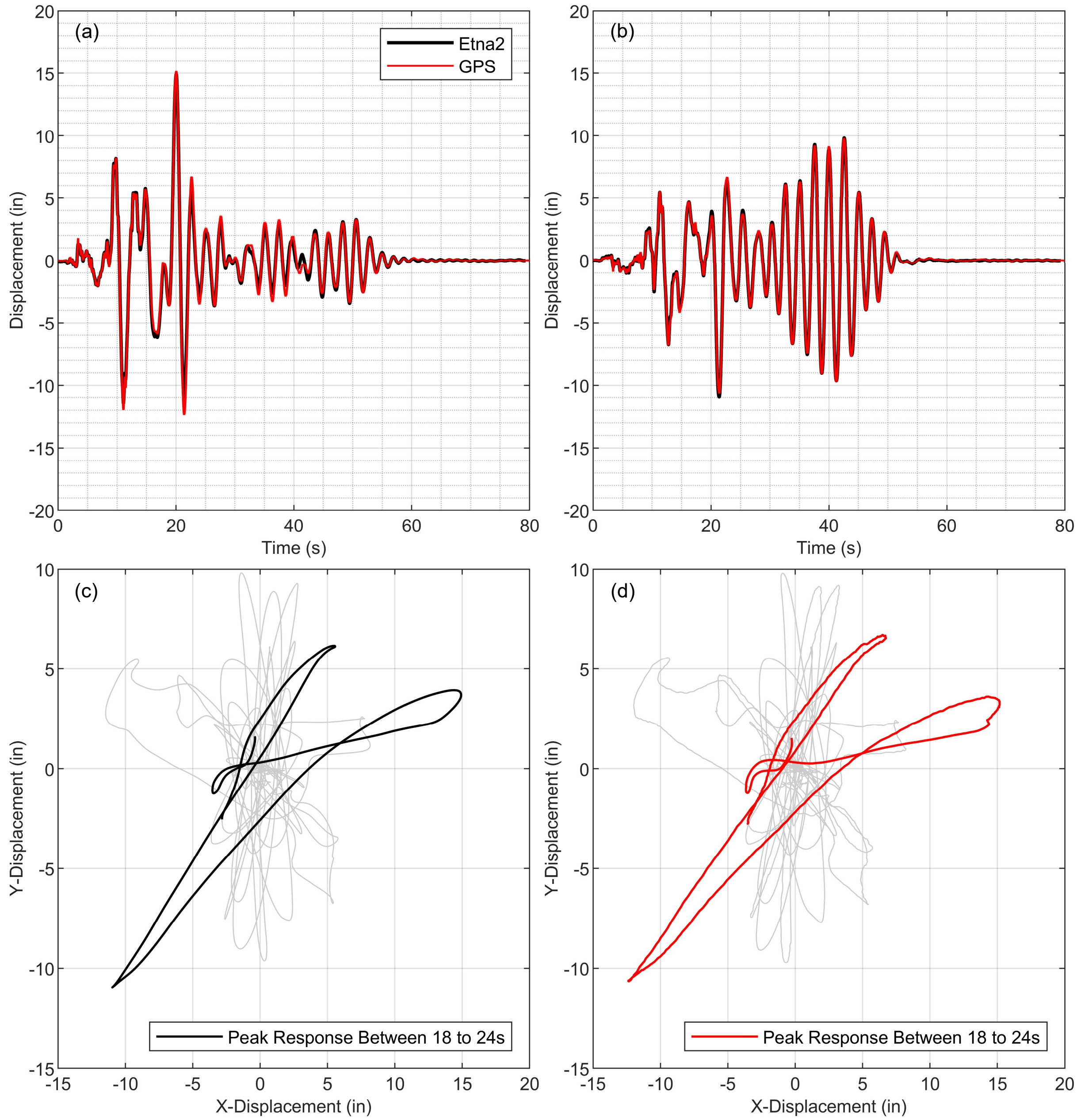


Figure 15. Time-history response a) X-direction b) Y-direction - X vs Y displacement plots c) Etna2 d) GPS

4 Conclusions

This paper presents the results of data collected as a part of payload study at UCSD outdoor shake table on a 10-story mass timber rocking wall building incorporating uplift friction dampers. Owing to the importance of displacements or more precisely interstory drifts for structural integrity, the study sheds light on the displacement response obtained from various types of sensors, such as accelerometers, string potentiometers in addition to GPS. A comparison of displacement response obtained through double integration of acceleration data from MEMS accelerometers and Force Balanced Accelerograph (Etna2) is compared with the benchmark displacement response of shake table controller and string potentiometers. The results highlight that Etna2 produces displacement and drift values closer to the benchmark displacement sensors, whereas, MEMS yield large errors in displacement response even with their best case high pass frequency filtering. While Etna2 still produces adequately accurate results, the errors in displacement for MEMS are more pronounced when subjected to multi-directional excitation. Due to accuracy of results obtained from Etna2, the roof displacement results from Etna2 are compared with the nearby GPS station on the roof. The GPS displacements when compared with that of benchmark Etna2 displacements exhibits good accuracy despite low sampling rate thus demonstrating the efficacy of GPS when other means of direct displacement measurements, such as string potentiometers, are unavailable.

5 Acknowledgement

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