A comparison of low-amplitude ambient and earthquake responses of a 64-story building in San Francisco, CA.

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ABSTRACT: Ambient and earthquake responses of a 64-story, instrumented, concrete core shear wall building with sloshing liquid dampers and buckling restraining braces are studied. In an earlier paper (Çelebi et al. 2013), only ambient data were used to identify dynamic characteristics. Recently, the 72-channel instrumental array recorded the 24 August 2014 M_w6.0 Napa, and the 21 July 2015 M_w4.0 Fremont, Calif. earthquakes – allowing comparison of the dynamic characteristics using ambient and earthquake data.

The peak accelerations of ambient and the larger (Napa) earthquake responses at the basement are 0.12 cm/s/s and 5.2 cm/s/s respectively – a factor of ~ 42. Similarly, at the 61st level, they are 0.30 cm/s/s (ambient) and 16.8 cm/s/s (Napa), respectively –a factor of ~56. Comparison of fundamental frequencies determined from normalized amplitude spectra for the NS (~0.3Hz), EW (0.27Hz) and torsional accelerations for the earthquake response are approximately 0.02-0.03 Hz smaller than those determined from ambient data. These small differences provides an argument that under stronger shaking of the building (e.g. design level), these differences in fundamental frequencies can be larger. These observations imply that dynamic response characteristics obtained from low amplitude shaking cannot be used in lieu of the same for strong shaking.

1 INTRODUCTION

One of the new landmark buildings of San Francisco, Calif., was, equipped with a 72-channel seismic monitoring system, and recorded its first earthquake related shaking during the Mw6.0 24 August 2014 event, herein called Napa earthquake. Prior to this earthquake several sets of ambient response data from the array of accelerometers deployed throughout the 64-story building (hereafter referred to as "the building") were acquired on demand.

The building was cooperatively instrumented by California Strong Motion Instrumentation Program (CSMIP) of California Geological Survey (CGS) and the Strong Motion Project of the U.S Geological Survey (USGS). For ease in following the rest of the paper, Figure 1 is adopted from www.strongmotioncenter.org (last visited 16 July 2015). Figure 1 shows (i) a photo of the building, (ii) the general core-shear wall, outrigger columns in one direction with BRB that links them to the core, and (iii) NS and EW vertical sections of the building.

A comprehensive detailed description of the building, performance based seismic design (PBSD) information, its acceleration response recording array and analyses of acquired ambient response data before any earthquake recording was available have been presented by Çelebi et al. (2013). Summarizing only relevant information from that paper:

1) The 188.31 m (617.83 ft) tall building is a concrete core shear wall structure with outrigger frame system and unique dynamic response modification features (such as two tuned sloshing liquid dampers [TSDs] and buckling restrained braces (BRBs) in EW direction and extending two locations between 28th -32nd and 51st -55th floors). The thickness of the core shear walls are 32" (81.3cm) between 1st (P4) level and 32nd level, 28" (71.12cm) up to 55th level and 24"(61.0cm) above 55th level. The wall to floor area percentages change from 2.4 to 3.9 %. Details of typical plans of several levels are shown in Figure 2 (also adopted from Çelebi et al. [2013 and www.strongmotioncenter.org (last visited 16 July 2015)].
2) It was cited as the tallest building (188.3 m [617.83 ft]) in the United States designed using performance-based seismic design (PBSD) procedures (*written information by MKA, 2012*).

3) The BRBs qualify the building to be the tallest performance-based seismic design (PBSD) in the world using BRBs (*written information by MKA, 2012*). Also, it is the first building in California to have two liquid tuned sloshing liquid dampers (TSD).
4) The building sits on a 3.66 m (12 ft) mat foundation on Rincon Hill of San Francisco – in very close proximity to the west (San Francisco) anchorage of the two suspension bridges of the Bay Bridge system.
5) The state-of-art, real-time continuous streaming capable recorder has a buffer from which it is possible to retrieve select lengths of ambient and/or seismic response data.

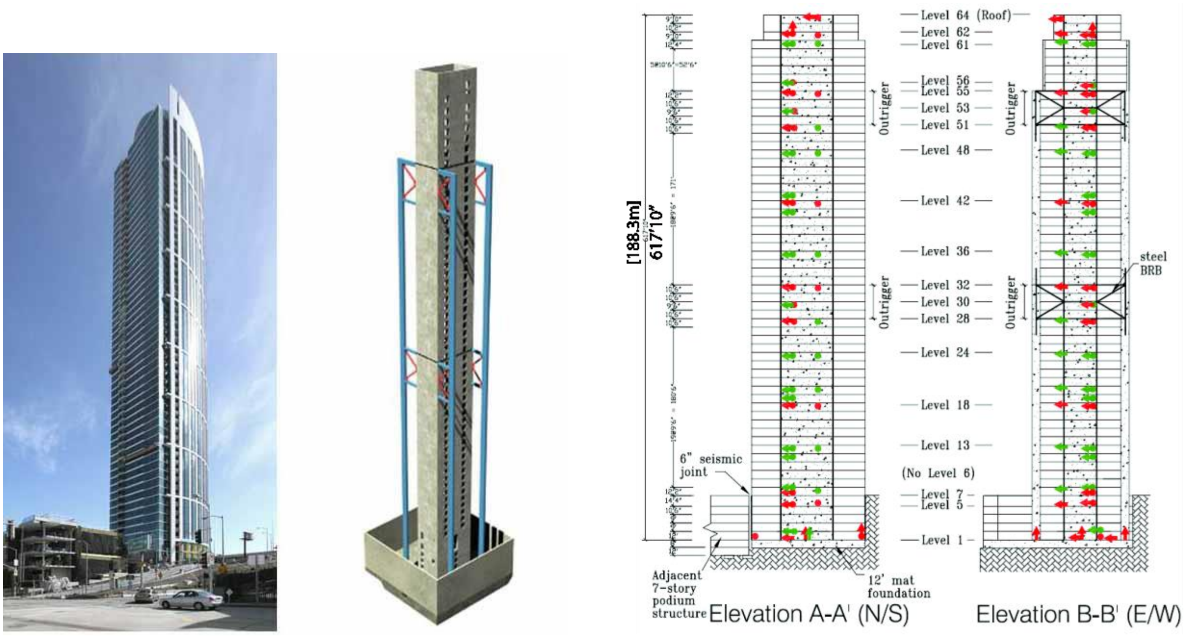

Figure 1. (Left) Picture of One Rincon Tower and its core skeleton with outrigger columns and attachment of BRB's to the core. (Right) Vertical sections of the building showing locations of the accelerometers along the height of the building (www.stongmotioncenter.org, last visited July 16, 2015). Red and Green colors refer to channels installed by the CSMIP and USGS NSMP respectively.

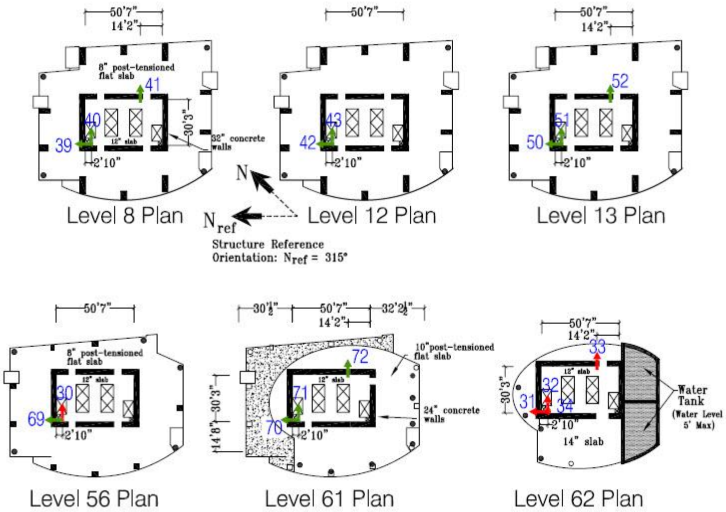

Figure 2. Typical plan views exhibiting sensor locations (green and red arrows), general dimensions and the core shear wall and outrigger columns (www.stongmotioncenter.org, last visited July 29, 2012). Note the building north reference direction (N_{ref}), which is termed NS in this paper. The thickness of core shear wall is 32" between Level 1 and 32, 28" between Level 32 and level 55 and 24" between Level 55 and Level 64 (Roof).

Some of the significant findings reported in the 2013 study (Çelebi et al., 2013) are:

1. At low-amplitude ambient excitations, no effects of the BRB's or TSD's were observed in the responses.
2. At low-amplitude ambient shaking:
    a. The first modal frequencies computed using spectral analyses and system identification methods, respectively, (*e.g.* NS [0.29Hz and 0.30 Hz], EW [0.28Hz and 0.27Hz] and Torsion [0.70Hz and 0.70 Hz]) compare well.
    b. The first modal damping percentages obtained by system identification method only are: NS (0.9%), EW (0.3-0.9%) and Torsional (0.4%). These are considered to be very low damping percentages but not abnormal for ambient data.

Within the last 24 months, the response of the building to the 24 August 2014 Mw6.0 Napa, Calif. and the 21 July 2015 Mw4.0 Fremont, Calif. earthquakes were recorded by all 72 channels. The epicenter of the Napa earthquake was 48.1 km from the building. For the larger Napa earthquake, the largest peak accelerations [a(g)] at ground level and within the building are .005g and .021g (for CH36 at the 64^{th} level), respectively. Largest displacement is 1.69 cm (CH36) [www.strongmotioncenter.org, last visited July 31, 2015]. Napa accelerations amplitudes are approximately an order larger than those of the Fremont earthquake which in turn are another order larger than the 2012 ambient data used in this study.

The objective of this paper is to study the Napa earthquake response records of the building, and comparing the results with major dynamic characteristics identified from the pre-Napa ambient data set and post-Napa Fremont earthquake records. The pre-Napa ambient data were analysed to identify modes and associated frequencies and damping. Not unexpectedly, the low-amplitude dynamic characteristics are considerably different than those used during design analyses of the building. Thus, data from the distinct acceleration levels, the pre-Napa ambient, Napa strong shaking and post-Napa smaller earthquake shaking, provide an opportunity to compare the behavior of the building before, during and after the Napa earthquake.

The analyses results serve as a baseline against which to compare even future stronger shaking responses (e.g. from expected Hayward fault earthquake or San Andreas fault families - both considered hazard from which risk to built environment in San Francisco and Bay area and Silicon Valley is always considered). It is documented that, in the next 30 years, there are 18% and 20 % probabilities for occurrence of a Mw 6.7or larger earthquake on the northern and southern sections of the Hayward faults, respectively (Field et al., 2015, *pers. comm*. D. Schwartz , 2015) .

In addition, studies similar to this one help to improve our understanding of the effectiveness of the response modification features at various levels of shaking, to evaluate the predictive capabilities of the design analysis tools, and to help improve similar designs in the future. As mentioned before, one major motivation was the acceleration records from the Napa earthquake.

In this study, we use spectral analyses techniques (amplitude spectra and spectral ratios) as described in Bendat and Piersol (1980) and coded in the software, MATLAB (Mathworks, 2013). We also used system identification techniques also available in MATLAB (Mathworks, 2013) based on Ljung (1987) to extract mode shapes and associated frequencies and damping. Finite element model (FEM) analyses were not performed. Descriptive references on FEM analyses performed by the designers were reviewed in the previous study (Çelebi et al., 2013).

2 DATA DESCRIPTION AND ANALYSES

2.1 Data organization and significant characteristics

Since there were no nearby earthquake records available until the 24 August 2014 Napa event, the analyses in the 2013 paper (Çelebi et al., 2013) were based only on ambient data acquired on demand from the buffer of the continuous streaming capable recorder. A continuous streaming buffer of the recording system is preferable to that from a triggering acceleration threshold as one-shot recording capability; otherwise, with data of shorter length, it is likely possible to miss some of the important behavioral aspects of the structure (e.g. beating effects). Figure 3 displays the beating effects observed from the continuous data but not the threshold triggered data set. Beating effects are discussed in more detail later in the paper. A summary of the particulars of the three sets of data used in this study is provided in Table 1.

Table 1. Description of data sets used in this study [sps= samples per second]. All data in this table are acquired from the buffer of continuous recording. (Building Coordinates: 37.7858N, 122.3921W)

Data Source	Coordinates	Date	Length (sec)	sps	Depth (km)
Pre-Napa Ambient	-	6/04/2012	120	100	
Napa earthquake (Mw6.0)	38.22N, 122.31W	8/24/2014	300	200	11.3
Fremont Eq. (Mw4.0)	37.58N,121.97W	7/21/2015	300	200	8.4

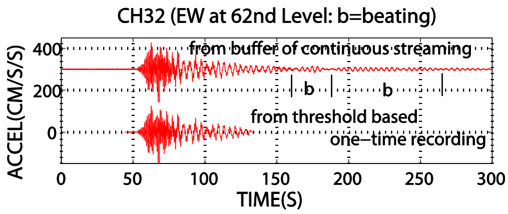

Figure 3. Comparison of continuous data versus threshold triggered data from the Napa data. Triggered data are obtained from www.strongmotioncenter.org (last visited September 2, 2015).

The distribution of accelerometers and their orientations are displayed in Table 2 (Çelebi et al., 2013). to easily follow accelerometer locations, orientations and numbering schedule.

Table 2. Distribution and labeling of horizontal channels along the height of the building (Çelebi et al., 2013).

			Channel Numbering (used in analyses)		
Level	H(m)	H(ft)	NS	EW1	EW2
1	0	0	37	38	6
5	12.34	40.5	7	8	9
7	16.71	54.83	10	11	
8	20.41	67	39	40	41
12	32	105	42	43	
13	34.9	114.5	50	51	52
18	49.38	162	12	13	14
19	52.27	171.5	44	45	
20	55.17	181	53	54	55
24	66.75	219.66	56	57	58
28	78.33	257	15	16	65
30	84.73	278	66	17	
32	91.13	299	18	19	20
36	103.72	337	59	60	61
41	117.7	384.5	46	47	
42	120.1	394	21	22	23
43	122.99	403.6	48	49	
48	137.46	451	62	63	64
51	146.46	480.5	24	25	67
53	152.55	500.5	68	26	
55	159.46	523.17	27	28	29
56	162.67	533.67	69	30	
61	179.22	588	70	71	72
62	185.21	607.83	31	32	33
64	188.31	617.83	35		36

Significant differences in relative amplitudes of the accelerations at 62nd level and 1st level from the

2012 ambient, 2014 Napa and 2015 Fremont earthquakes are displayed in Figure 4.

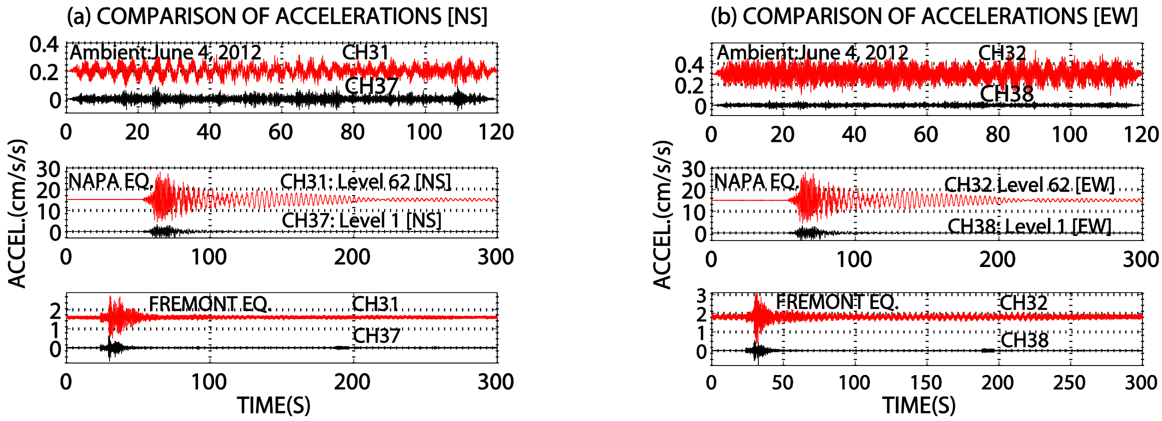

Figure 4. Equally scaled for earthquake, time-history of accelerations are compared for pre-Napa ambient (June 4, 2012), Napa earthquake and Fremont earthquake for (a) NS [CH31 at 62 level and CH37 at 1st level] and (b) EW [CH32 at 62nd level and CH38 at 1st level]. The figures indicate that, although small in amplitude, Napa earthquake accelerations are at visually least ~ 150 (~15/0.1) times the ambient accelerations. Note the different horizontal scales of June 4, 2012 ambient data.

The significant differences between the level 1 and 61th and 62nd level accelerations for the NS, EW and torsional directions are displayed in Figure 5. Note that for the NS and EW 61th and 62th level, the beating effects are observed again. As indicated, beating effects are addressed later in the paper.

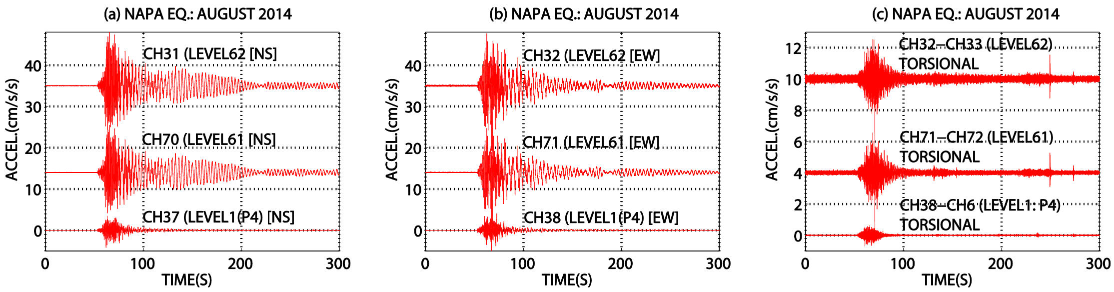

Figure 5. Equiscaled (a) NS, (b) EW and (c) torsional acceleration time-history plots each for 61st, 62nd and 1st levels. Note the beating effect at 61st and 62nd floor accelerations in the NS and EW directions.

2.2 System identification and mode extraction using Napa earthquake data

System identification method, N4Sid, within MATLAB (Mathworks, 2013) are used to extract modal frequencies, modal critical damping percentages (ξ) and mode shapes. For the first 3 modes the extracted frequencies and damping are tabulated in Table 3. It is noted that critical damping percentages (ξ) for the largest shaking (Napa earthquake) data set are consistently lower than 3% for NS, EW1 and torsional modes. When EW2 direction is included, ξ exceeds 3% for two EW2 modes. The below 3% of critical damping in most cases is consistent with findings of analyses of data from other tall buildings (e.g. a tall building in Osaka from the M9 2011 Tohoku earthquake shaking). This observation is important because during design process and development of design response spectra, generally, the smallest critical damping percentage used is 5%. Therefore, lowering the damping from 5% to 3 % can result in more conservative design than that for 5%.

Table 3. First three modal frequencies, modal critical damping percentages for NS, EW1, EW2 and Torsion.

	NS	EW1	EW2	TORSION
Modal Frequencies (Hz)				
Mode 1	0.29	0.26	0.26	0.68
Mode 2	1.27	1.11	1.25	1.98
Mode 3	2.62	2.45	2.65	3.67

Modal Damping (%)				
Mode 1	1.2	2.2	4.1	0.8
Mode 2	1.4	1.2	6.02	2.8
Mode 3	.46	1.9	1.8	1.2

The mode shapes extracted are shown in Figure 6. Frequencies and damping are shown within each frame. The mode shapes are normal as can be expected and do not indicate any interference (e.g. abrupt changes) from BRB's or slosh dampers.

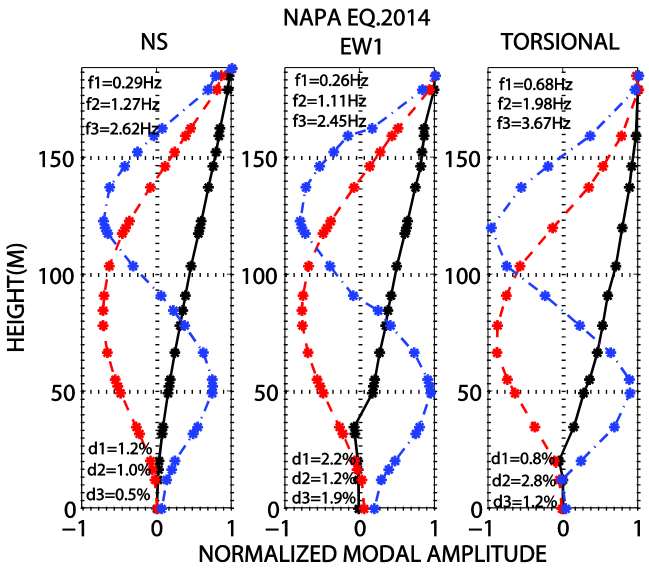

Figure 6. Three mode shapes and associated modal frequencies and damping percentages extracted from NS, EW and Torsional acceleration.

2.3 Amplitude spectra and spectral ratios for 3 events

For sake of brevity, we present normalized amplitude spectra and normalized spectral ratios of the three events for 0-2Hz frequency band only (Figure 7). In computing amplitude spectra and spectral ratios we use accelerations at the 62nd level and level 1. The resulting computed fundamental frequencies (~0.29 Hz for NS and EW, and ~0.68 Hz for Torsional) are similar for all three events. However, the spectral ratios indicate the expected trend – which is, for the low shaking (ambient), for both NS and EW 2nd mode frequencies are higher than the next level shaking (Fremont earthquake) which in turn are higher than the Napa earthquake. This confirms previous experiences of extraction of frequencies from observed data where the frequency gets lower as the shaking level gets higher.

2.4 Beating

Beating effects, observed in several building response records in the past, occur when translational and torsional frequencies are close to one another and the structural system has low damping (Boroschek et al., 1990, 1991, Çelebi, M., 2004, 2006). Also, beating effects may explain one of the reasons for elongated durations of "replenished" shaking when repetitively stored potential energy during coupled translational and torsional deformations turns into repetitive vibrational energy. Thus periodic, repeating and resonating motions ensue. The beating becomes severe if the system is lightly damped. The beating effect period (T_b) is computed using the relationship: $T_b=2T_1T_t/(T_1-T_t)$ given by Boroschek and Mahin (1991). In this relationship, T_1 and T_t are fundamental translational and torsional periods, respectively. In this case, [if T1=3.45s (f1=0.29Hz, T1=1/f1=3.45s) and Tt=1.47s (f1=0.68Hz, Tt=1/.68)] Tb is computed to be around 5 seconds but visual observation (Figures 3 and 5) indicate much larger beating periods (~30-40s). It is possible that the ~5s may occur during stronger shaking. Thus we conclude that computed beating periods are not consistent with visually observed ones. Nonetheless, the main point is that beating occurs in this building as evidenced by the Napa records from continuous data. This is important to note as such beating effects prolong the responses and therefore increase the number of large and small cycles of responses. Thus, even the increased number of smaller amplitude cycles becomes important due to possible low-cycle fatigue that can result in nonlinear behaviour at joints.

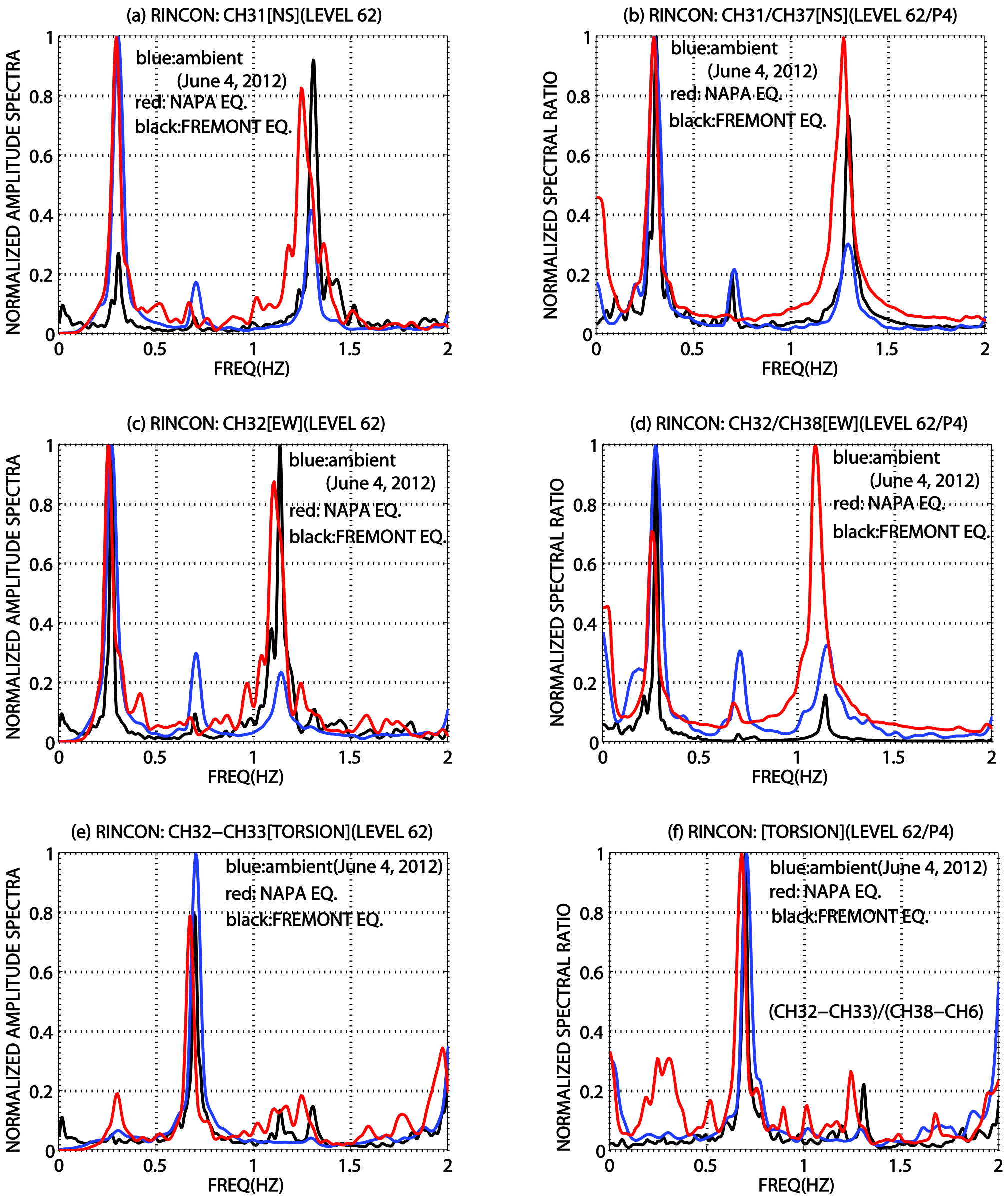

Figure 7. Comparison of 0-2Hz band normalized amplitude spectra from 62nd level accelerations (a) NS[CH31], (c) EW[CH32] and (e) Torsional [CH32-CH33] and normalized spectral ratios from amplitude spectra of 62nd and 1st (P4) level accelerations (b) NS[CH31/CH37], (d) EW[CH32/CH38] and (f) Torsional [(CH32-CH33)/(CH38-CH6)].

3 CONCLUSIONS

Study of ambient and earthquake records from 72-channels of an array deployed in a 64 story core shear wall San Francisco building with response modification features indicate that:

1. There are small differences between the frequencies extracted from ambient versus earthquake data even though the latter are one or two orders larger in amplitudes of acceleration.

2. Critical damping percentages obtained by system identification method using the Napa data with larger acceleration amplitudes much lower than used in practice. This observation is consistent with those inferred from studies of other tall buildings.
3. At low amplitudes of excitation, the response modification features do not appear to have altered the response characteristics (e.g. mode shapes, damping percentages and frequencies) of the building. The effectiveness of these modification features should be carefully evaluated from larger amplitude response data obtained during future earthquakes.
4. Beating effects are visually observed from the Napa records obtained by continuous recording. However, the beating periods do not check with the estimation formula established by previous studies.

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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