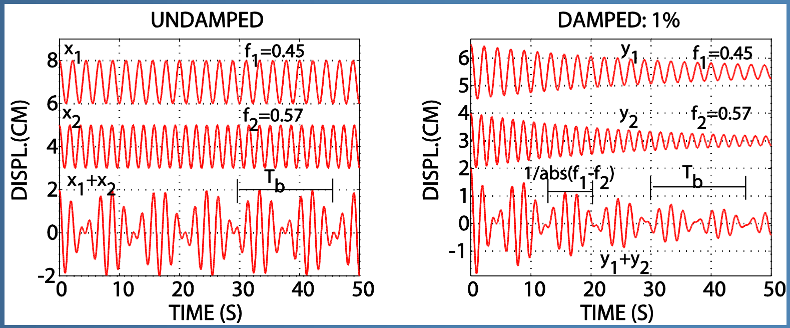
SIGNIFICANCE OF BEATING OBSERVED IN EARTHQUAKE RESPONSES OF BUILDINGS

MOTIVATION: In a cursory survey of several textbooks on structural dynamics, it can be seen that beating effects have not been included in their scopes. On the other hand, as more earthquake response records from instrumented buildings became available, it also became evident that the beating phenomenon is common.



DEFINE BEAT PERIOD WIKIPEDIA (next)

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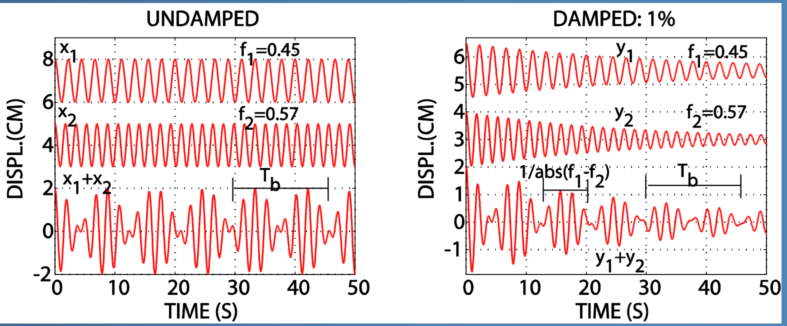
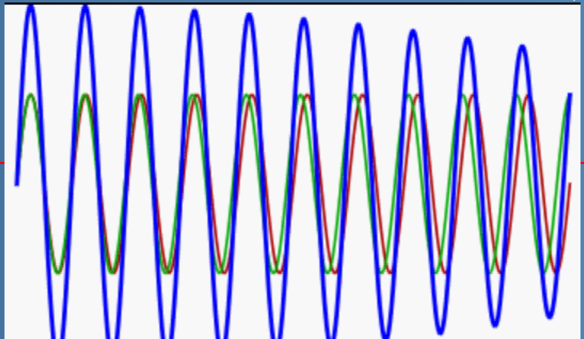
Figure 1 demonstrates two simple harmonic signals with constant frequencies (0.45 and 0.57 Hz) and with and without light damping ratio of 1 %, are summed to demonstrate the beating phenomenon.



The "beat frequency" (fb) - as it is generally referred to in acoustical physics - is denoted by the absolute value of the differences in frequencies (f1-f2) that cause the phenomenon [https://en.wikipedia.org/wiki/Beat (acoustics)]. The "beating period" (Tb) is twice the inverse of beat frequency (Tb=2/fb) as shown in Figure 1. Throughout this paper, the beating period will be computed by the following equation (see also Boroschek and Mahin, 1991):

Tb=1/Fb=2/fb=2/abs(f1-f2)=2T1T2/abs(T1-T2)



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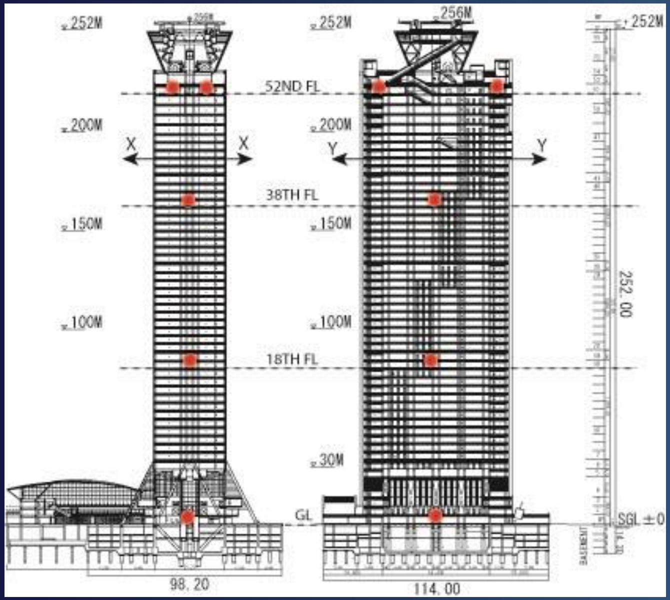
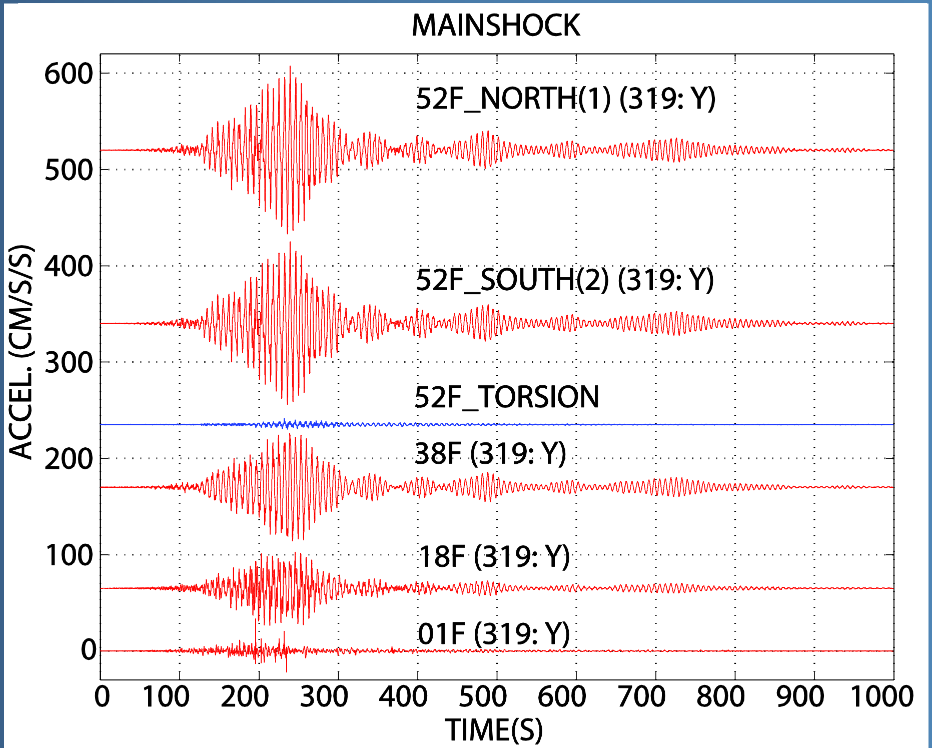
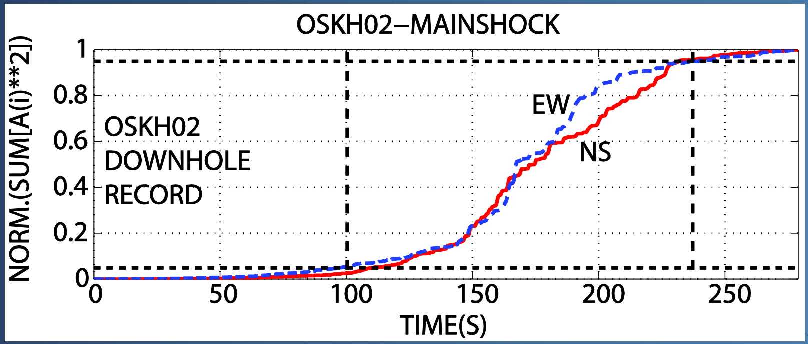
SIGNIFICANCE OF BEATING OBSERVED IN EARTHQUAKE RESPONSES OF BUILDINGS



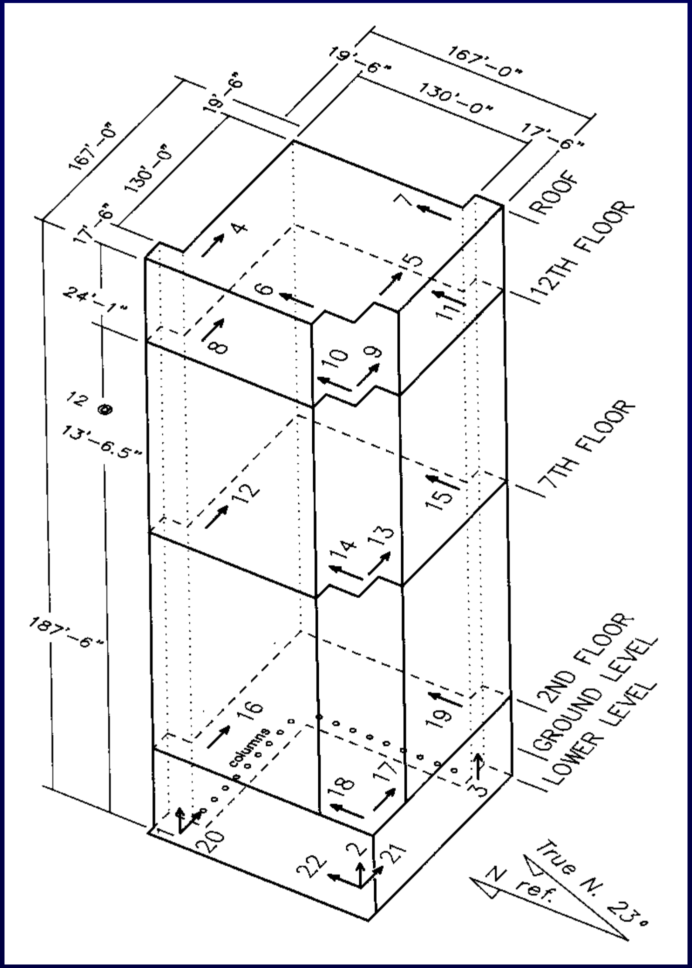




SIGNIFICANCE OF BEATING OBSERVED IN EARTHQUAKE RESPONSES OF BUILDINGS

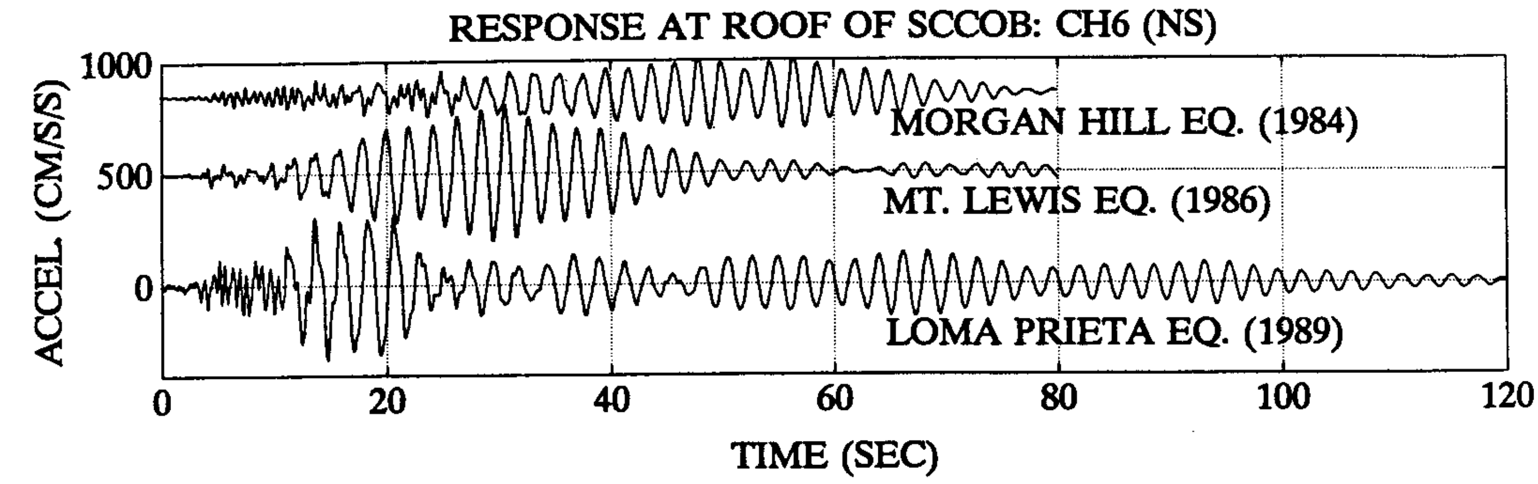
- Objective: Beating observed in the recorded responses of a tall building in Japan and another in the U.S. are examined in this paper.
- What is beating?: (1) Beating is a periodic vibrational behavior caused by distinctive coupling between translational and torsional modes that may have close frequencies, and is prominent in the prolonged resonant responses of lightly–damped structures. (2) Resonance caused by site effects also contributes to accentuating the beating effect.
- Methods: Spectral analyses and system identification techniques are used herein to quantify the periods and amplitudes of the beating effects from the strong motion recordings of the two buildings.
- *Why study?: Quantification of beating effects is a first step towards determining remedial actions to improve resilient building performance to strong earthquake-induced shaking*.

EXAMPLE(1a): SCCOB: A 13-story, 56 m tall, 51 m x 51 m in plan, moment-resisting, steel-framed structure [built in 1970 according to UBC 1970 provisions]. There are 6 column lines in each direction.



EXAMPLE (1b): SCCOB: NOTE FREQ & DAMPING

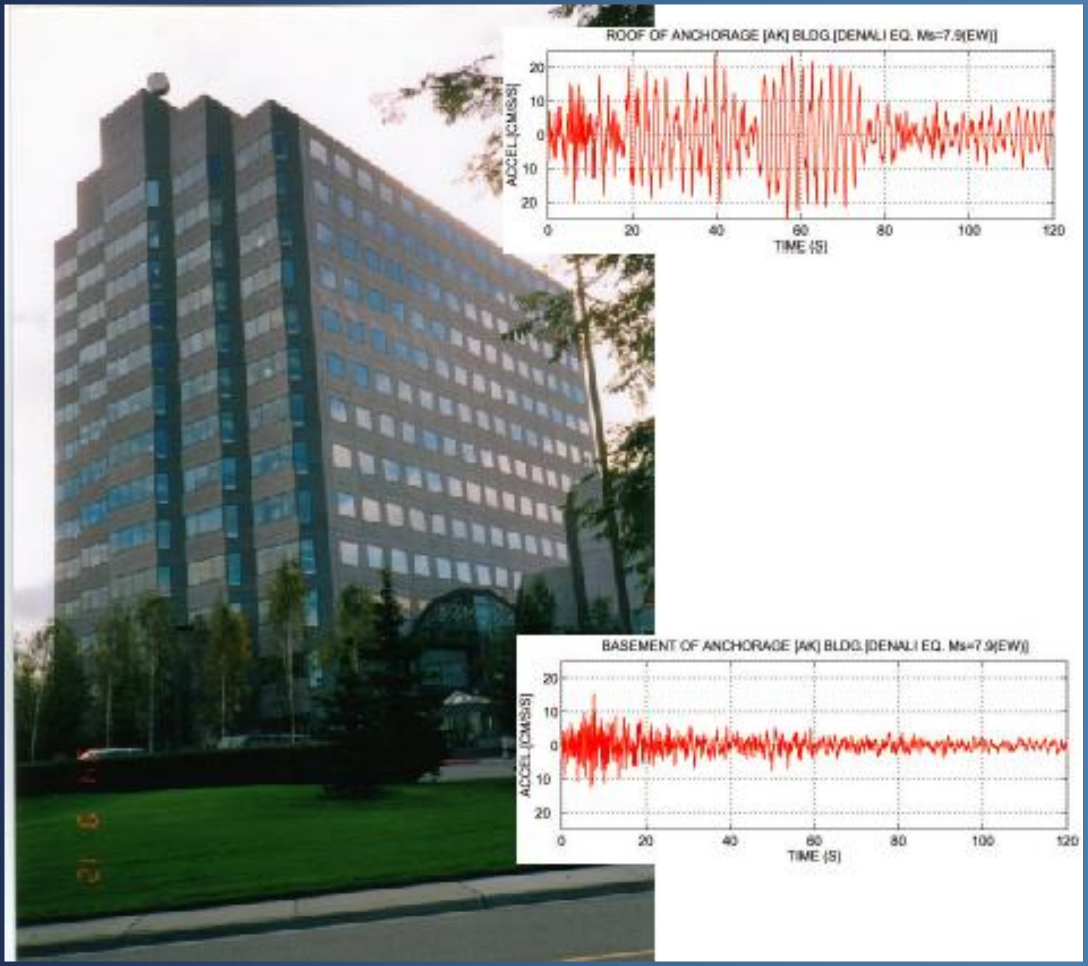
		Earthquake		
		Loma Prieta	Morgan Hill	Mt. Lewis
Peak Acceleration (G)	Roof (NS)	0.34		0.32
	Roof (EW)	0.34	0.17	0.37
	Base (NS)	0.10	0.04	0.04
	Base (EW)	0.09	0.04	0.04
Translational	Period [T (sec)]	2.22	2.17	2.08
	Frequency [f (Hz)]	0.45	0.46	0.40
	Damping [ξ (%)]	2.70	0.17	2.12
Torsional	Frequency [f (Hz)]	0.57	0.59	0.58
	Damping [ξ (%)]	1.69	1.70	1.72



- Inherent low-damping of the building
- Closely-coupled torsional-translational mode that causes beating
- Basin effect and site characteristics MAY contribute to resonating excitation

Example2: 14-story BP Building in Anchorage. AK

Denali EQ of 11-02-2002 Mw=7.9, d=286 km.



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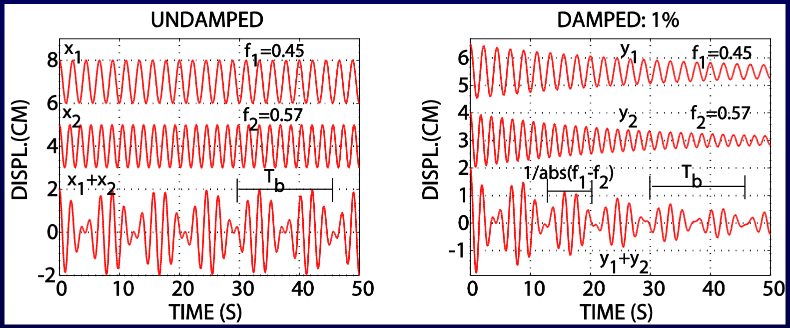
What is beating effect?

Repetitively stored potential energy during the 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.



What are the implications of the beating effect?

- Elongated shaking due to beating effect takes its toll on the structural system – particularly if the structure is brittle and old (*e.g.* historical building).
- Repetitive shaking accentuates fatigue and low-cycle fatigue.
- Beating cycles provide discomfort to occupants.

Examples:

We are going to concentrate on two cases (buildings) in this paper:

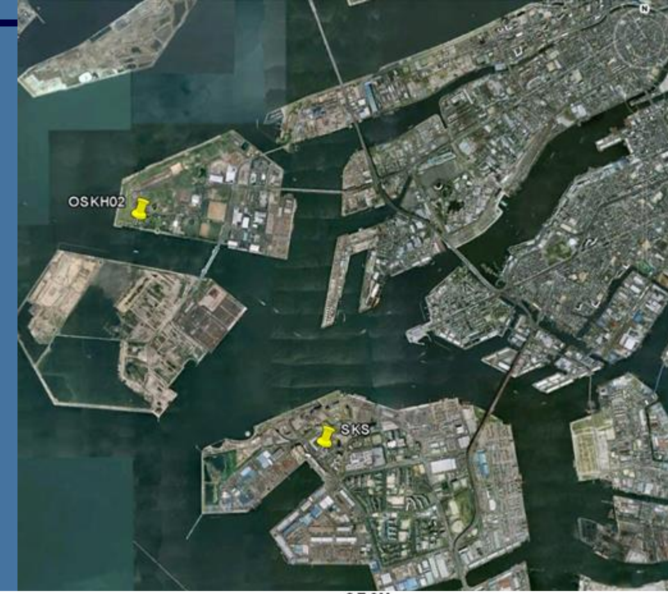
Case 1: SKS Building in Osaka during the Tohoku Event of March 11, 2011 (Mw9.0)

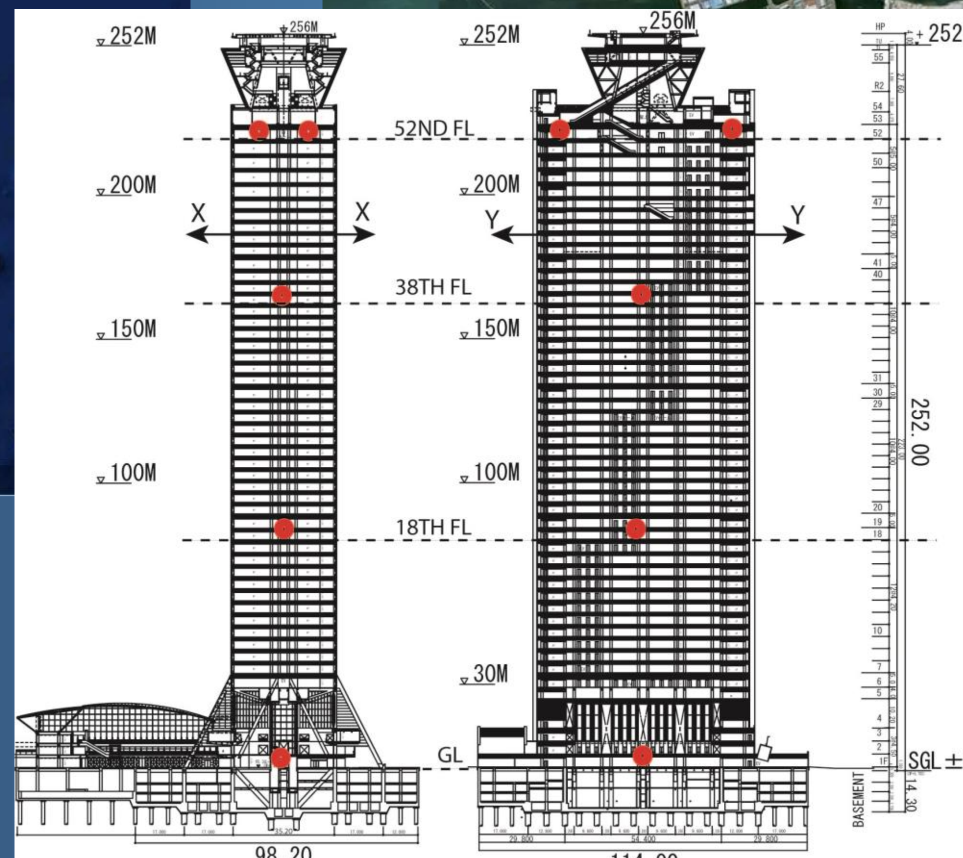
[Çelebi, M., Okawa, I., and Kashima, T., S. Koyama, and M. Iiba, 2014, Response of a tall building far from the epicenter of the March 11, 2011 M=9.0 Great East Japan earthquake and its aftershocks**, The Wiley Journal of The Structural Design of Tall and Special Buildings**. (2012 Published online in Wiley Online Library: wileyonlinelibrary.com/journal/tal). DOI:10.1002/tal.1047 and in volume: 23, 427-441 (2014)]]

Case 2: Atwood Building in Anchorage, AK

[Çelebi, M., 2006, Recorded Earthquake Responses from the Integrated Seismic Monitoring Network of the Atwood Building, Anchorage, (AK), **Earthquake Spectra**, v.22, no.4, pp **847-864, November 2006**

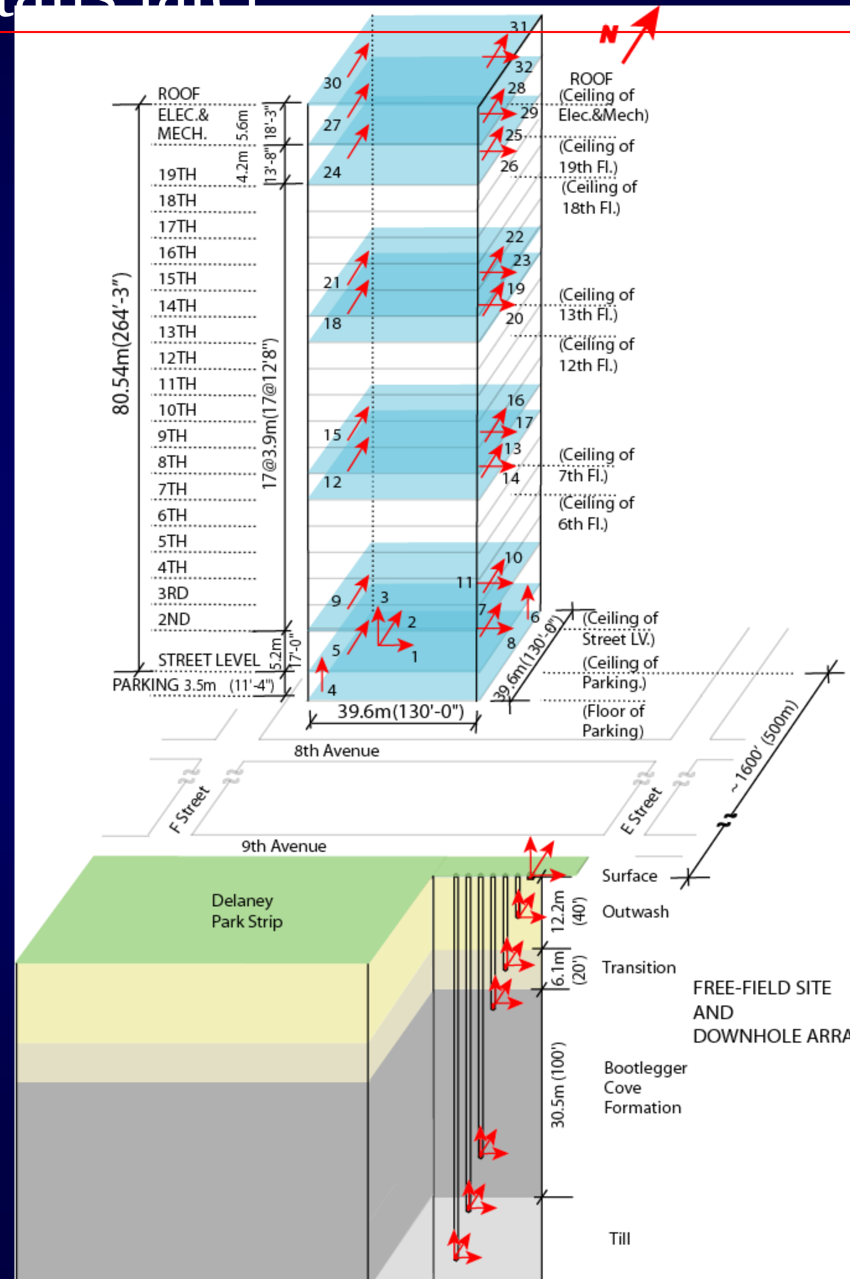
Case 1:Building in Osaka Bay ~767 Km from epicenter of March 11, 2011 main-shock



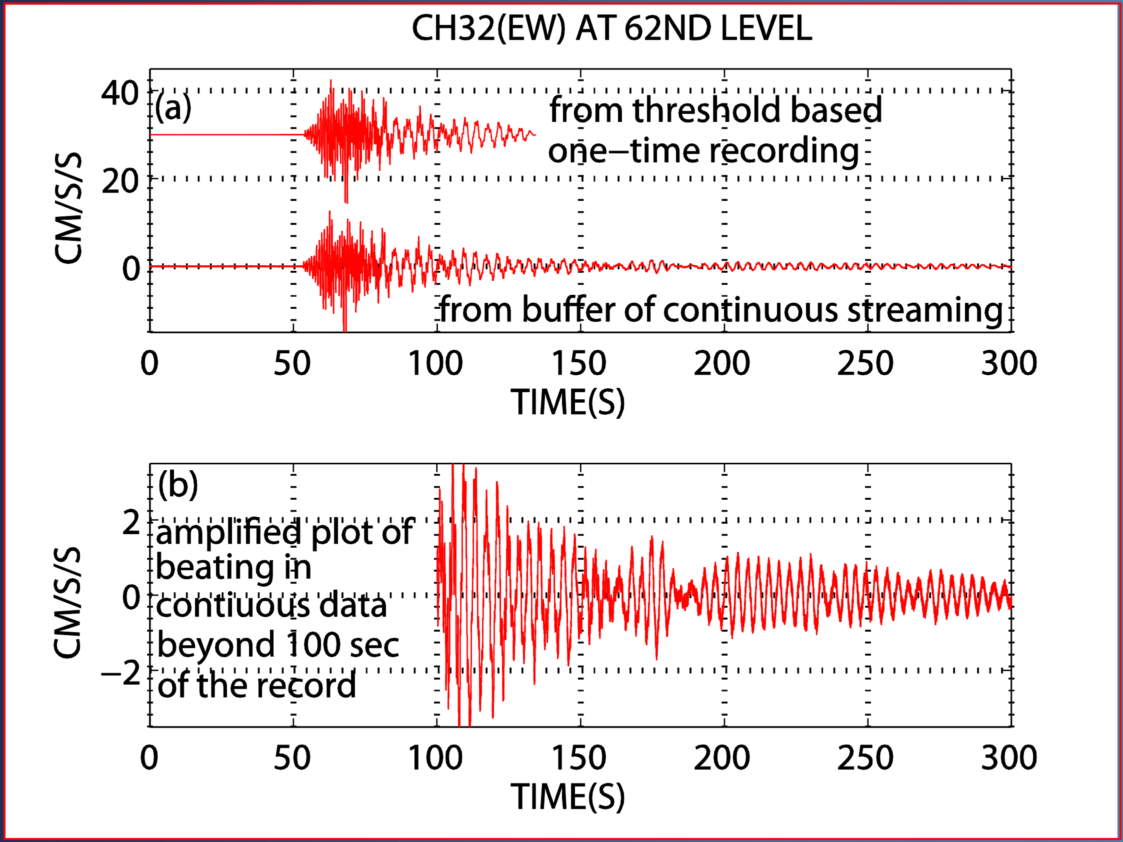


- 256 m tall (55 stories+3 story basement)
- Construction finished in 1995 (pre-1995 code, pre-(KIK-NET/K-NET). Vertically irregular, steel, moment-frame (rigid truss-beams/10 floor). No shear walls around elevator shafts
- 60-70 m long piles below foundation

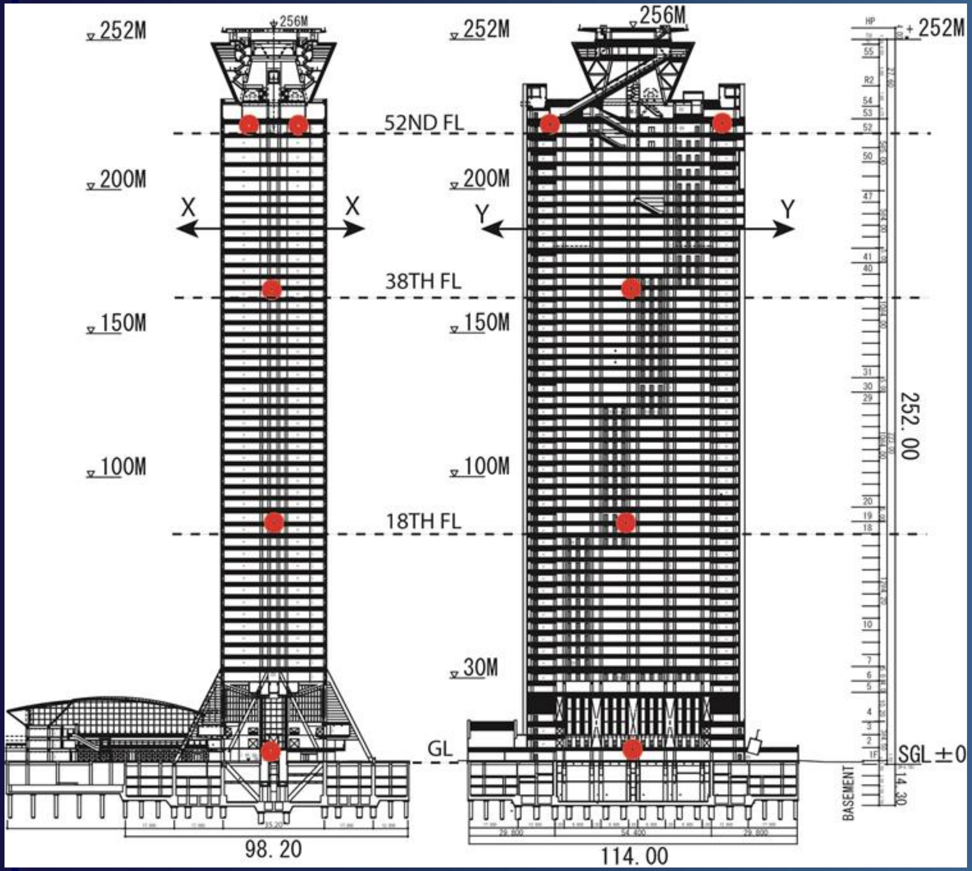
Case 2: Case Atwood Building in Anchorage, AK. More details later



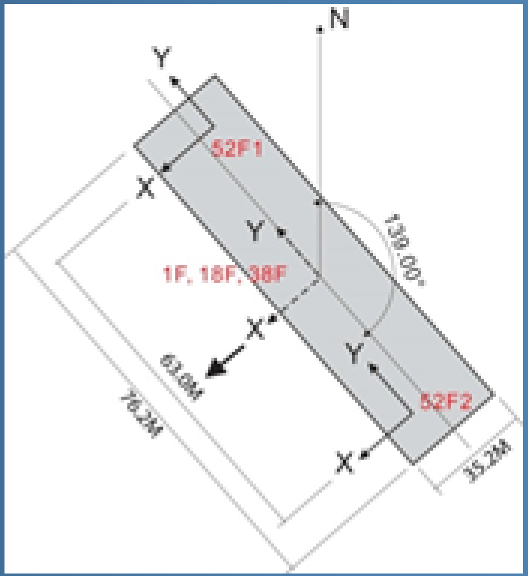
Before we go on, an important issue:Benefit of continuous recording vs threshold base recording



Case 1:

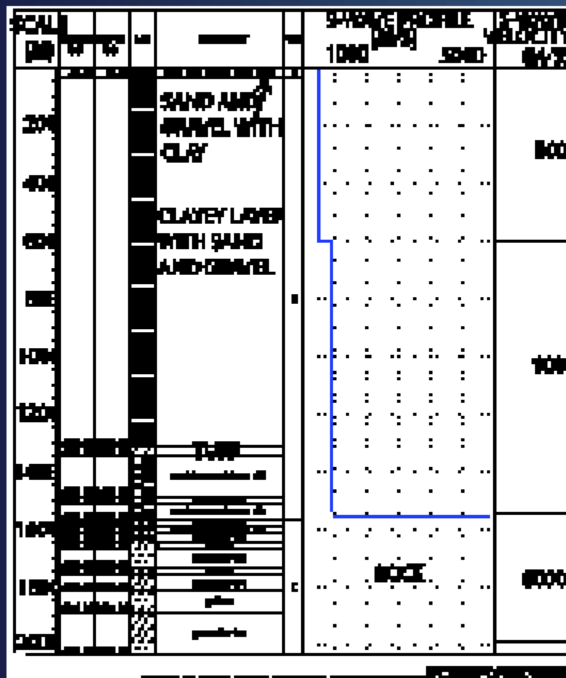


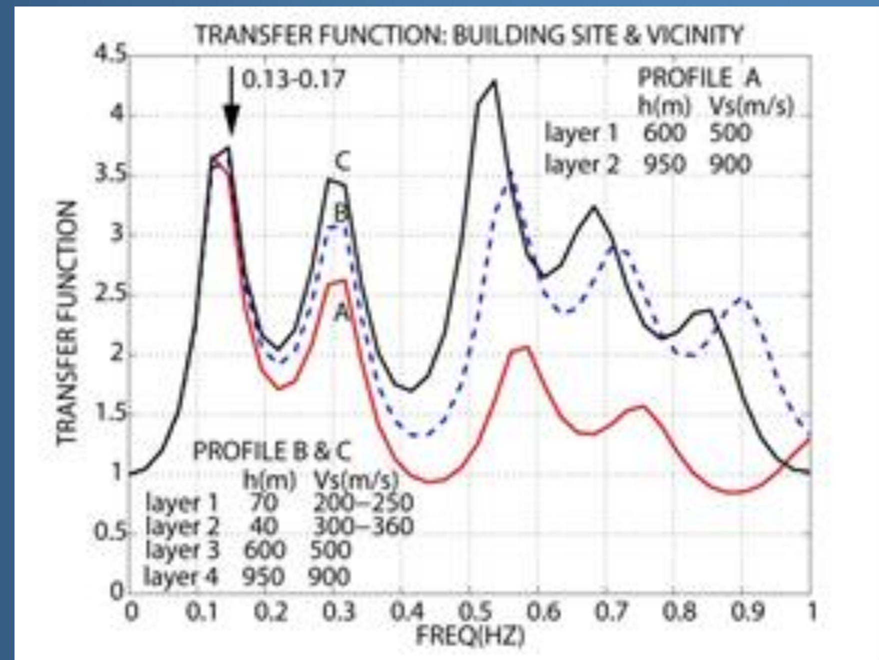
252M
256M
52ND FL
200M
X
X
Y
Y
38TH FL
150M
100M
18TH FL
30M
GL
SGL ±0
252.00
14.30
BASEMENT
98.20
114.00



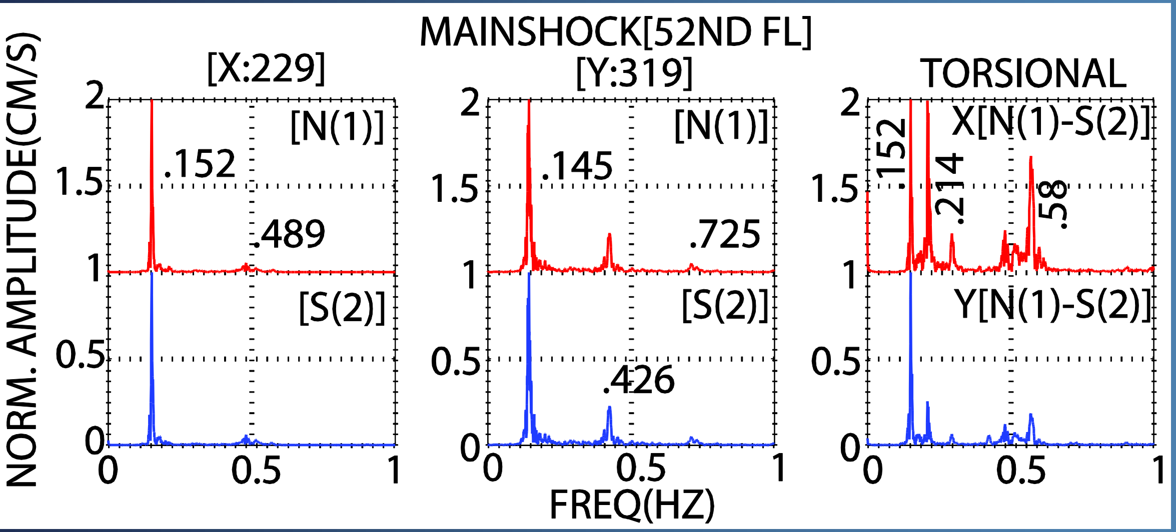
N
Y
X
52F1
1F, 18F, 38F
52F2
139.00°
63.0M
76.2M
35.2M

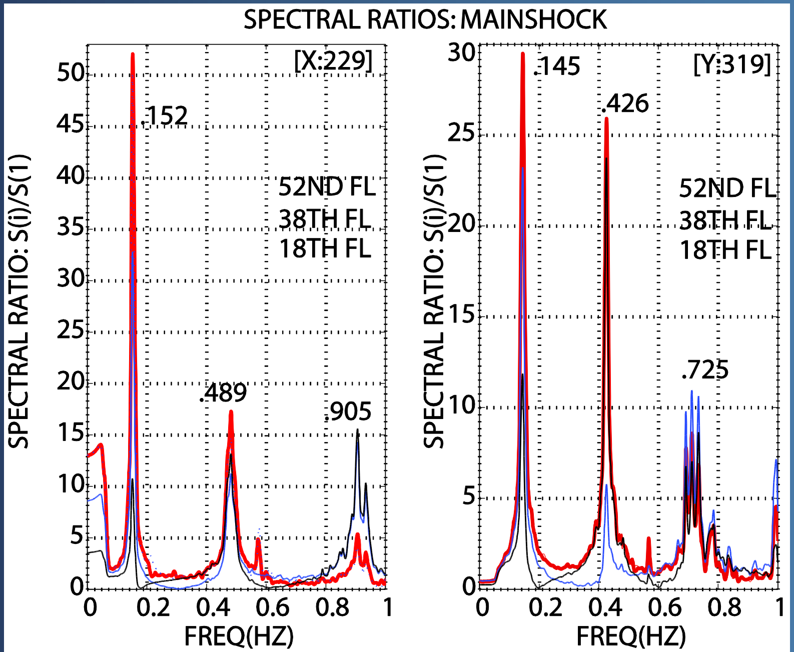
Case 1: Site Amplifications





Case 1: Amplitude Spectra & Transfer Function
Note: Narrow spectra implies low damping

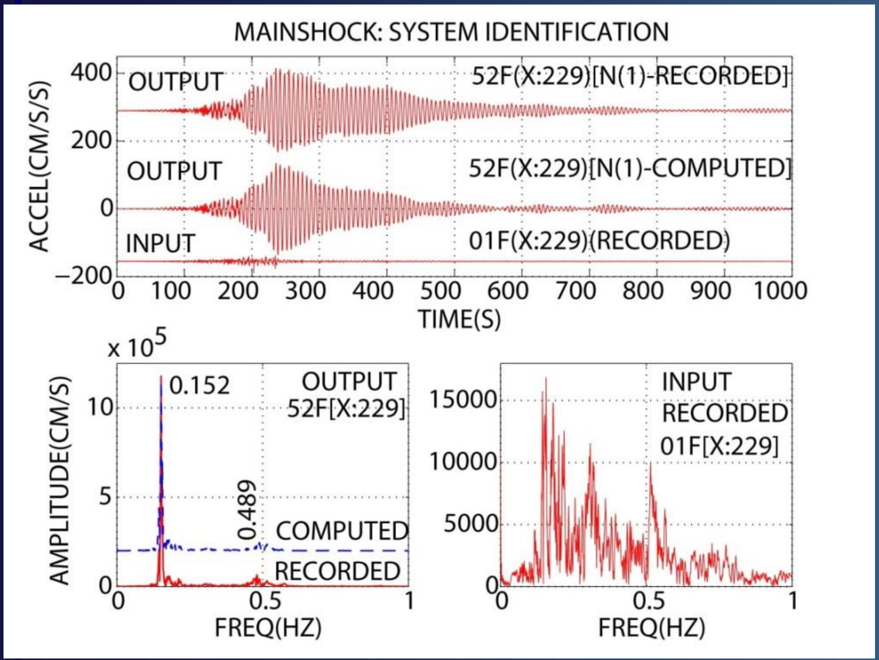


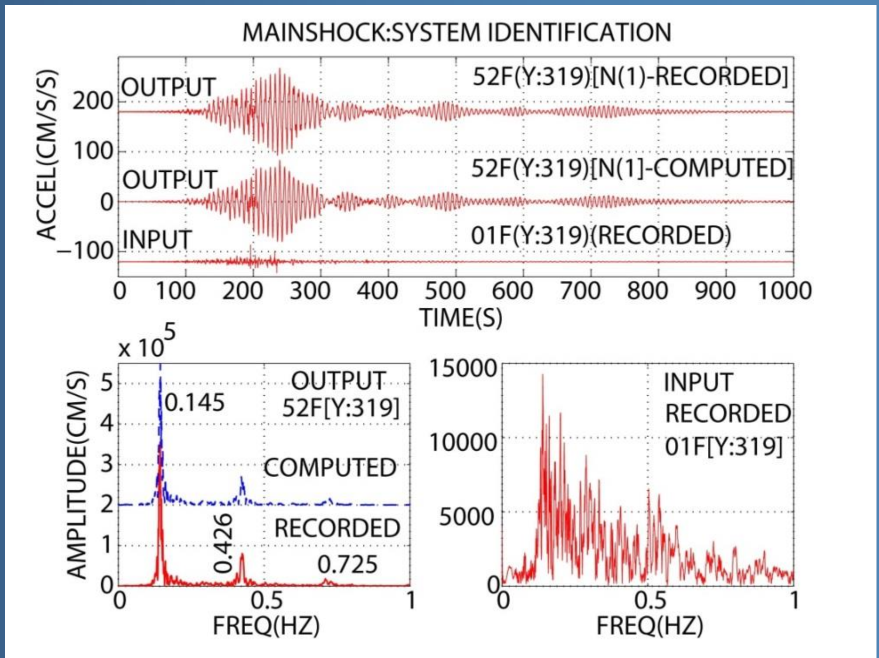


Case 1: Design Analysis, Spectral Analysis & System Identification Results (note: narrow amplitude spectra – low damping)

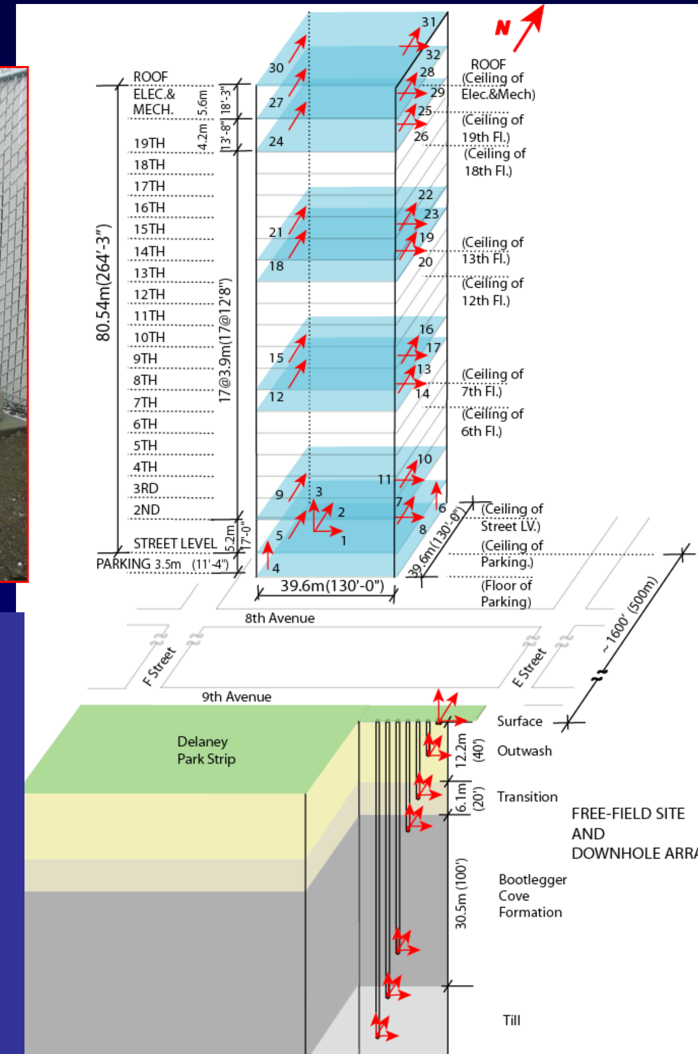
ORIENTATION	X[229]			Y[319]			TORSION	
MODES	1	2	3	1	2	3	1	2
ANALYSES DURING DESIGN								
Freq(Hz) [T(s)]	.1887 [5.3]			.1724 [5.8]			.2703 [3.7]	
MAINSHOCK [EVENT 1] (Spectral Analyses)								
Freq(HZ) [T(s)]	0.152 [6.58]	0.489 [2.06]	0.905 [1.11]	0.145 [6.90]	0.426 [2.34]	0.725 [1.38]	.213 [4.69]	.58 [1.72]

SYSTEM IDENTIFICATION							
MAINSHOCK [EVENT 1] (System Identification)							
Freq(Hz) [T(s)]	0.1524 [6.56]	0.4887 [2.05]	N/A	0.1447 [6.91]	0.4264 [2.35]	0.7250 [1.38]	
Damping (ξ)	0.012	0.020		0.016	0.001	0.020	



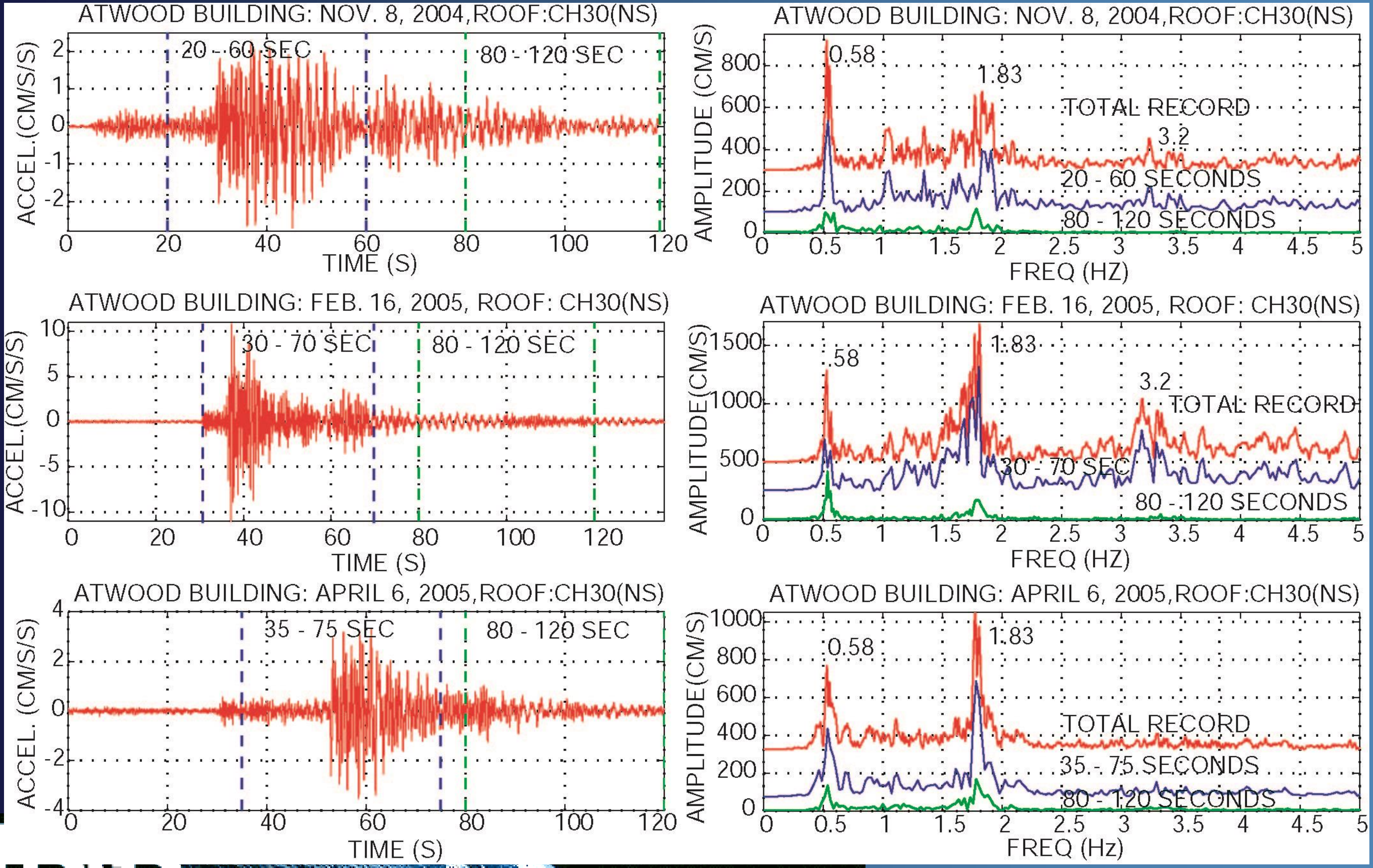


Case 2: Case Atwood Building in Anchorage, AK.



- **The Atwood Building - a 20-story, steel framed building.**
- **Single story basement and a RC foundation w/o piles**
- **130'x130' (39.6 mx39.6m)in plan with 48'x48' (14.6mx14.6m) in plan center steel shear walled core. Designed according to 1979 UBC.**
- **Site of the building: underlain by ~100-150 ft (30.5-45.7m) thick soil layer known as Bootlegger Cove Formation.**

REPEATABILITY: 3 EARTHQUAKES STRUCTURAL FREQUENCIES



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Case 2:ATWOOD BLDG: System Identification
6 April 2005: Tazlina Glacier EQ.,Mw4.9, d=189km

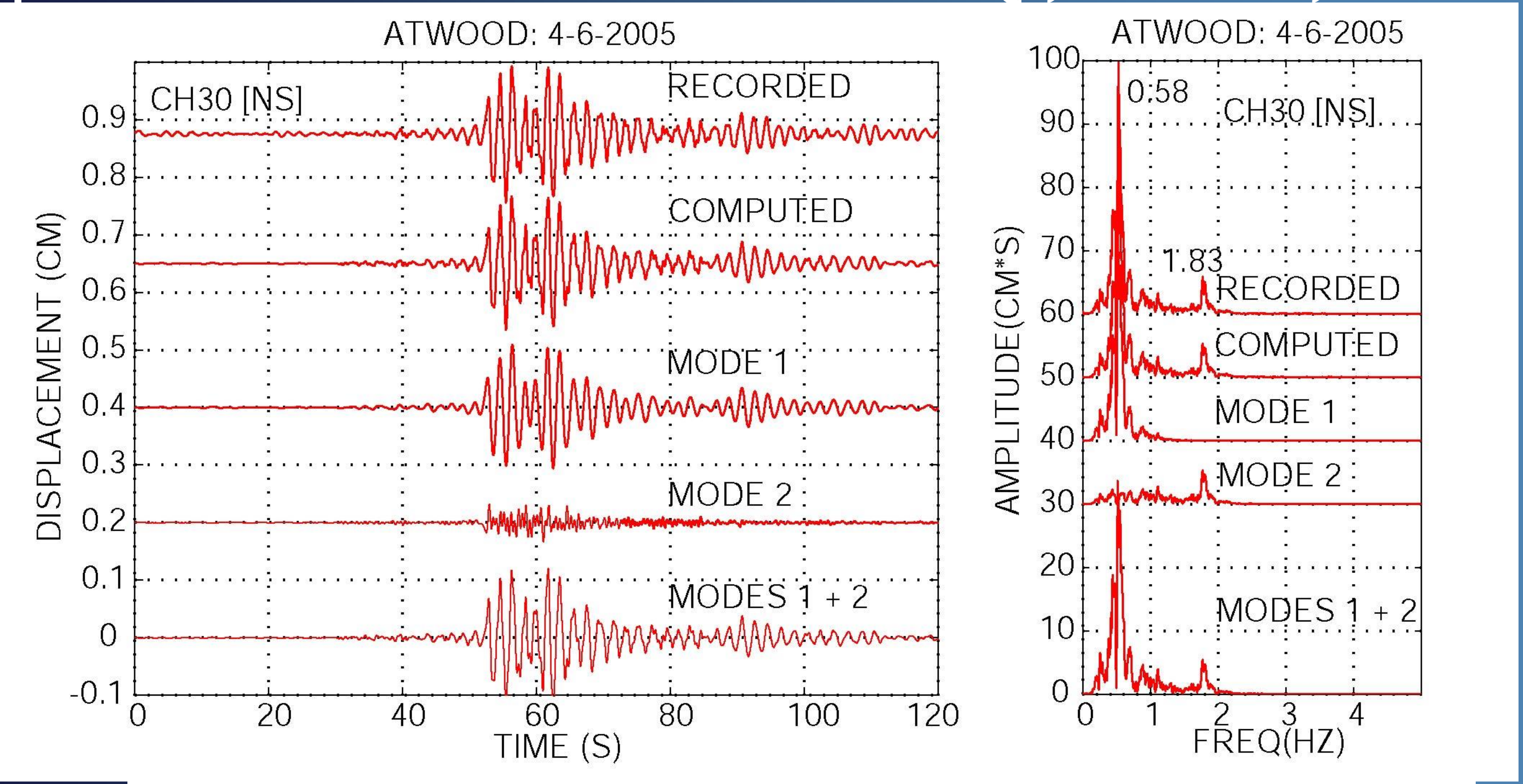
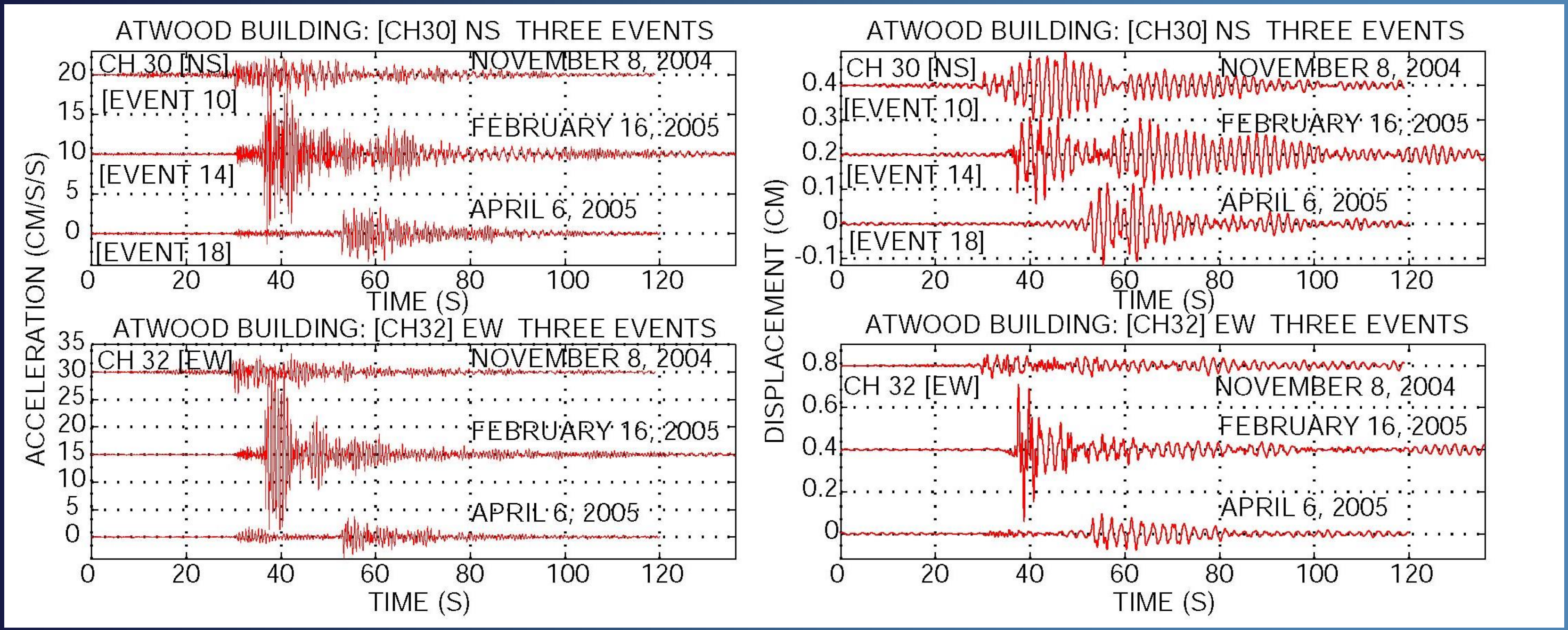


Table 2. Dynamic characteristics determined by system identification (ξ=modal damping)

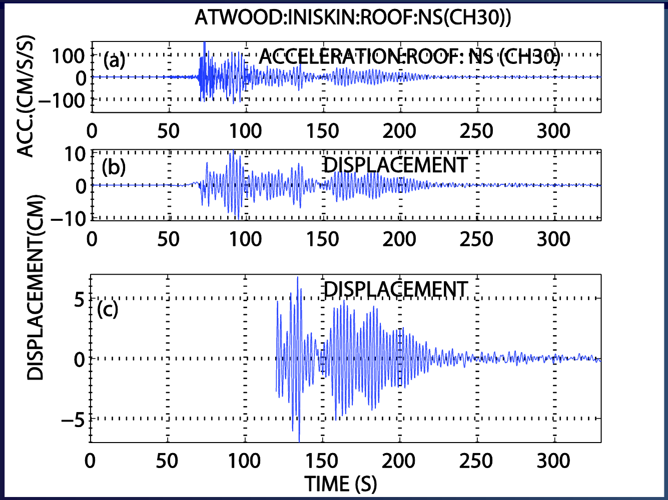
	NS			EW		
Mode	f (Hz)	T (s)	ξ (%)	f (Hz)	T (s)	ξ (%)
1	0.58	1.73	2.7	0.47	2.13	4.2
2	1.83	0.55	2.7	1.53	0.65	2.8
3	3.6	0.28	5.1	2.9	0.35	2.4
4	4.9	0.20	3.6	4.3	0.24	4.1

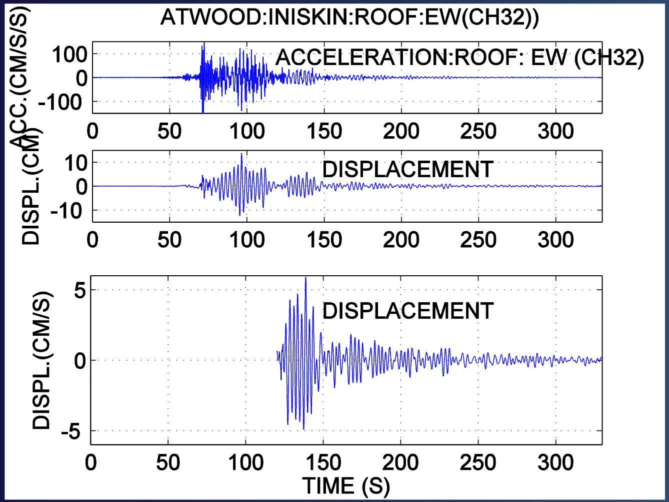
REPEATABILITY: 3 EARTHQUAKES
BEATING EFFECT: $T_b=2T_1T_2/(T_1-T_2)$



	Translational		Torsional		Beating	
	f_1 (Hz)	T_1 (s)	f_t (Hz)	T_t(s)	f_b (Hz)	T_b (s)
Combination 1	0.55	1.8	0.6	1.66	0.023	42.7
Combination 2	0.47	2.1	0.6	1.66	0.063	15.8
Combination 3	0.47	2.1	0.55	1.82	0.037	27.3

Case 2: New Data: January 24, 2016 Iniskin EQ, Mw7.1,d=262km





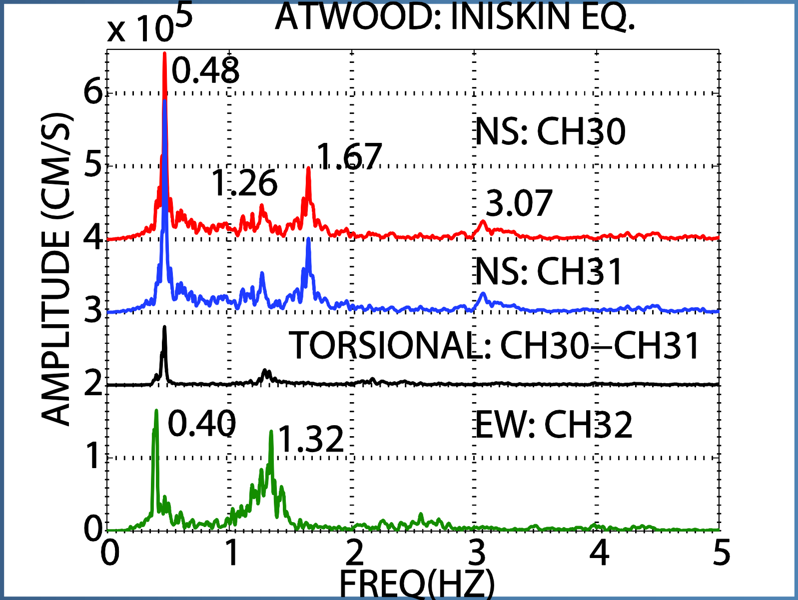


Table 5. NS, EW and torsional modal frequencies and damping percentages computed by system identification.

	Mode 1		Mode 2		Mode 3	
	f(Hz)	ξ (%)	f(Hz)	ξ (%)	f(Hz)	ξ (%)
NS1	0.47	1.47	1.65	2.52	3.12	1.98
EW	0.40	1.34	1.35	2.71	2.58	4.51
TOR	0.47	0.12	1.33	3.17	2,17	4.77

Conclusions

- Although only two cases are presented in this paper, beating effects are often observed in records of prolonged responses of numerous tall or mid-rise buildings. In this paper, we draw attention to this real physical phenomenon that was observed in a building in Japan and another in the US. Quantification of the presence of beating can stimulate finding solutions to eliminate it, or to decrease the possible adverse effects that it may cause.

Ghahari, S.F. , **Ç**elebi, **M**., Taciroglu, E., 2016, Shaking in the Atwood Building in Anchorage, Alaska during the Mw7.1 Iniskin, Alaska earthquake of January 24, 2016. **A video**: https://www.usgs.gov/media/videos/shaking-frontier-building-anchorage-alaska-during-mw71-earthquake-january-24-2016, or https://ipds.usgs.gov/WPP/Bibliodata.aspx?IP=IP-074469 or http://gallery.usgs.gov or **http://gallery.usgs.gov/videos/1018#.Vv6beRMguC4**