Using Acceleration Sensors to Learn and Improve the Modeling of Damping in Buildings

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UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA

Blume Center Stanford

PEER

Last week in Puerto Rico...

StEER
STRUCTURAL EXTREME EVENTS RECONNAISSANCE

Eduardo Miranda

The best way to learn about the seismic response and performance of structures is to study the response of real structures during real earthquakes (i.e., the ultimate full-scale shake table tests with realistic models and boundary conditions)



Examples of buildings in Puerto Rico instrumented by UPRM and the PRSMP

Eduardo Miranda

Learning from Instrumented Structures

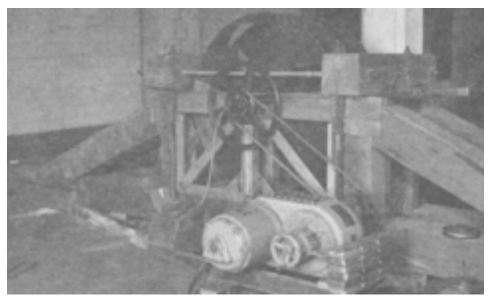
If a structure is instrumented it offers a UNIQUE opportunity to improve and validate of analytical models, but also to learn about the fragility of foundations, structures and nonstructural components.

I was sort of dragged into Earthquake Engineering on Sept 19, 1985, almost 35 years ago, and I believe we don't do enough of this. We don't instrument enough structures, we don't study enough those that are instrumented, etc.

For 20 years now I have been a strong advocate of structural instrumentation and serve in advisory committees in ANSS/USGS and CSMIP and I try to learn as much as possible on the ultimate test: real structures subjected to real earthquakes.

Early attempts to learn about damping in buildings

Bank of America Bldg, San Jose
J.A. Blume and L. Jacobsen, 1935



Four-Story RC Building on
Commercial St in Los Angeles
J.L. Alford and G.W. Housner, 1953

Hollywood Storage Building
Oct 1993 Long Beach Aftershock
R.R. Martel and M.P. White, 1951

A common approach to initiate this learning is to pose questions

Sample of questions that I’ve asked my self

- Is it adequate to model damping as viscous damping?
- Should I use modal damping or Rayleigh damping ?
- If modal damping, same damping ratio for all modes?
- What value should I use?
- It is height dependent?
- Same value for steel and reinforced concrete?
- Same value for all lateral resisting systems?
- How about damping in higher modes?
- Is damping amplitude-dependent?

There is a need for new improved damping recommendations for the seismic analysis of buildings that provide guidance on some of these questions. Instrumented buildings offer a UNIQUE opportunity to answer this kind of questions.

Apparent dichotomy on damping in buildings

$$\xi_{wind} \ll \xi_{earthquake} \text{ ?}$$

Damping for Wind Loading

"In wind applications, damping ratios of 1 percent and 2 percent are typically used in the United States for steel and concrete buildings at serviceability levels, respectively, while ISO (1997) suggests 1 percent and 1.5 percent for steel and concrete, respectively."

(Source: Commentary ASCE 7-10)

Apparent dichotomy on damping in buildings

$$\xi_{wind} \ll \xi_{earthquake} \quad ?$$

Damping for Seismic Loading

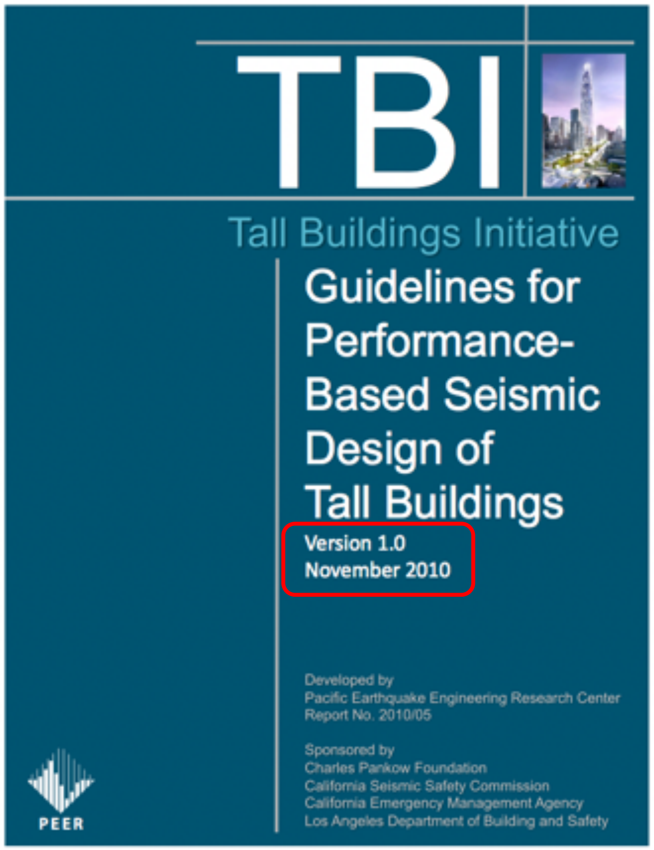
18.6.2.1 Inherent Damping

Inherent damping, β_I, shall be based on the material type, configuration, and behavior of the structure and nonstructural components responding dynamically at or just below yield of the seismic force-resisting system. Unless analysis or test data supports other values, inherent damping shall be taken as not greater than 5 percent of critical for all modes of vibration.

(Source: ASCE 7-10)

Myth: Tall Buildings have 2.5% damping

Damping for Seismic Loading



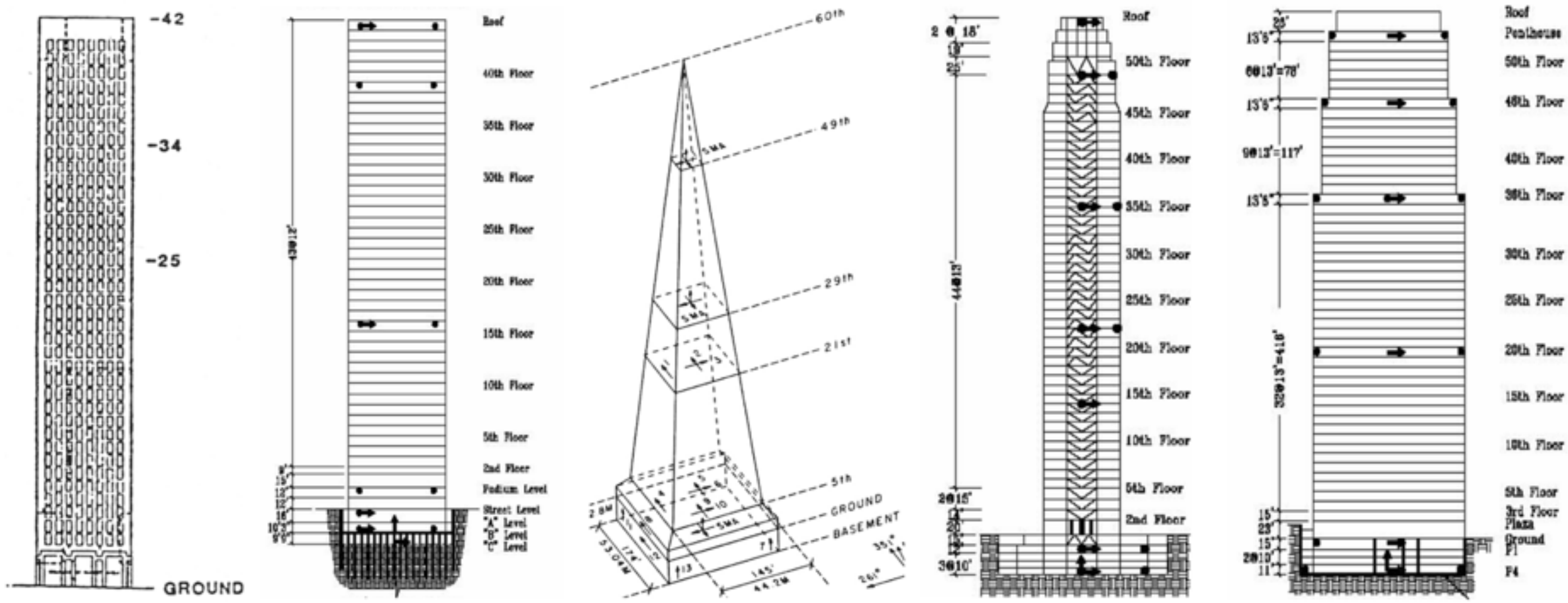
"A number of studies have attempted to characterize the effective damping in real buildings. These studies range from evaluation of the recorded response to low- amplitude forced vibrations to review and analysis of strong motion recordings. Using data obtained from eight strong motion California earthquakes, Goel and Chopra (1997) found that effective damping for buildings in excess of 35 stories ranged from about 2% to 4% of critical damping. Using data obtained from Japanese earthquakes, Satake et al. (2003) found effective damping in such structures to be in the range of 1% to 2%. Given this information and the impossibility of precisely defining damping for a building that has not yet been constructed***, these Guidelines recommend a default value of 2.5% damping for all modes for use in Service Level evaluations***. "

(Source: PEER, 2010)

Examples of Buildings Analyzed

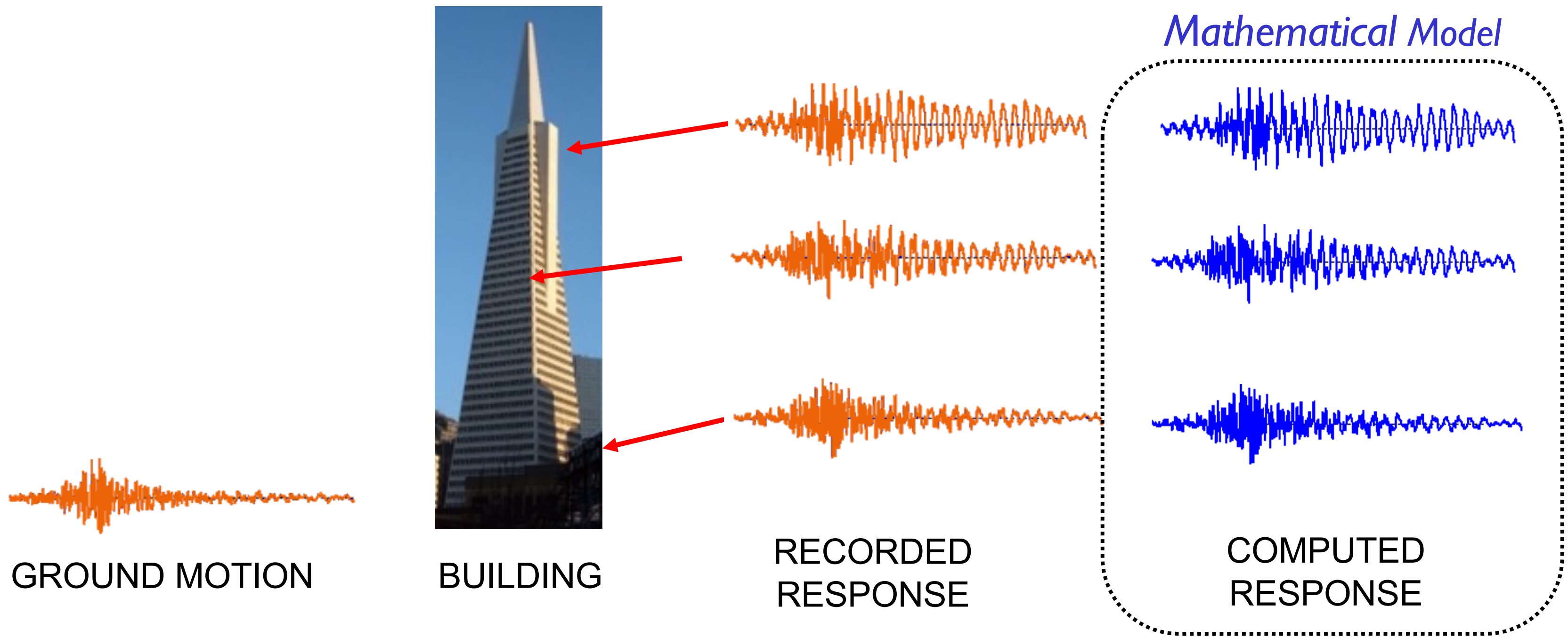
PEER

Examples of Location of Instrumentation of Buildings Analyzed



Tall buildings are typically instrumented at four or more levels

Inferring damping ratios from recorded motions



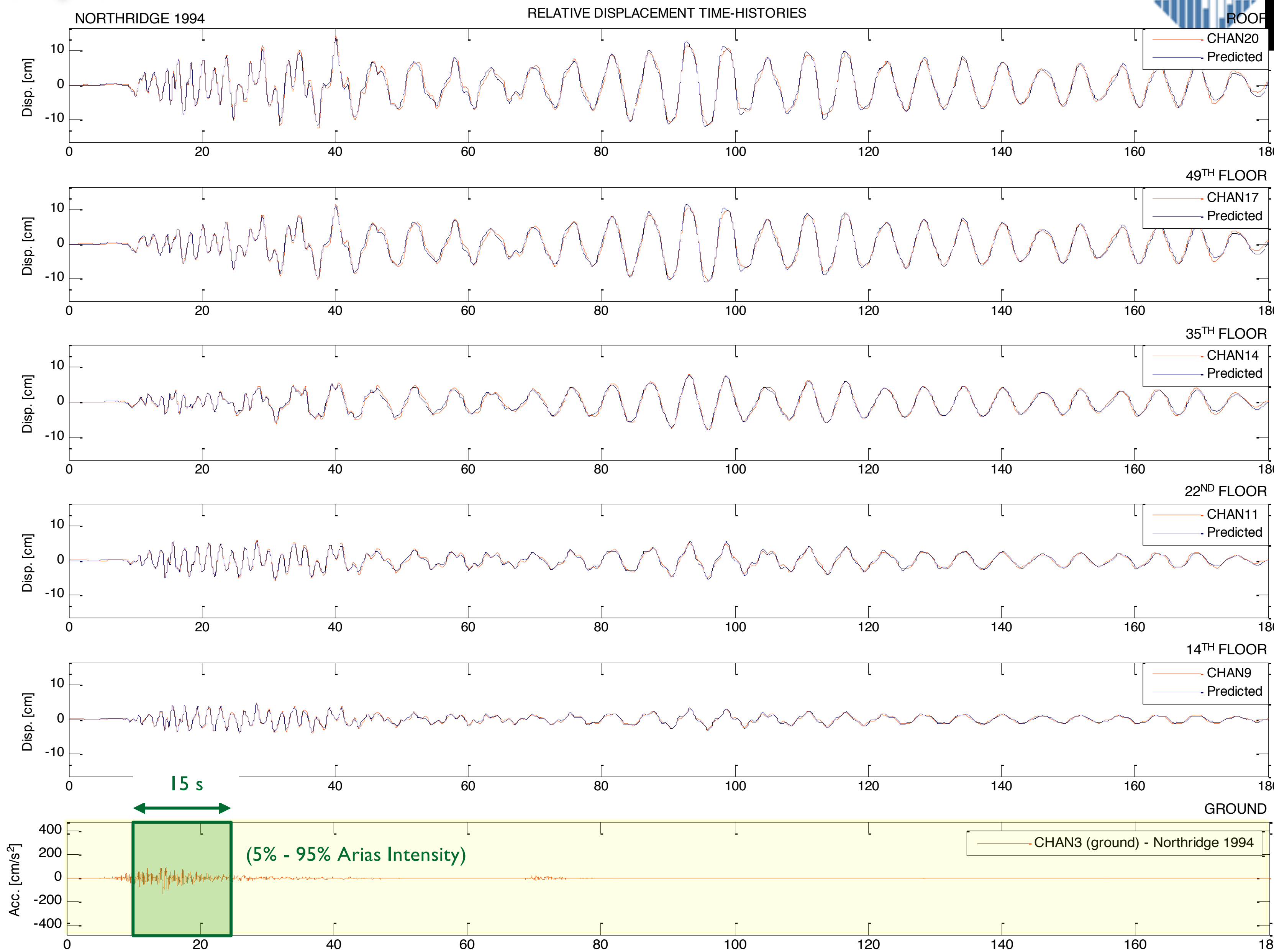
Basics of how we do it:

- We use a parametric system identification technique in the time domain

OPTIMIZATION: Minimize the error between the recorded and predicted responses

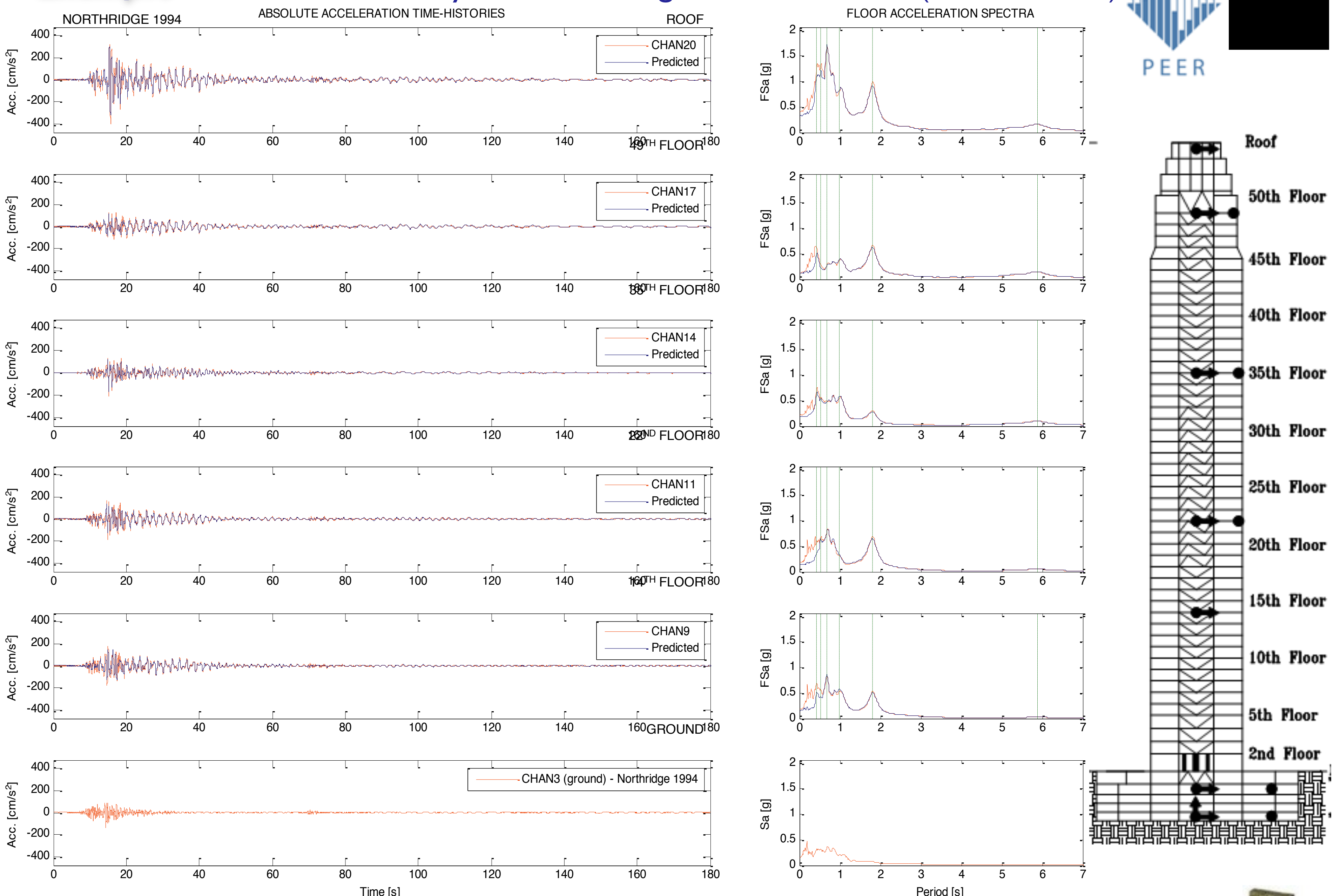
Example

52-Story Office Building in downtown LA (NS Direction)



Example

52-Story Office Building in downtown LA (NS Direction)



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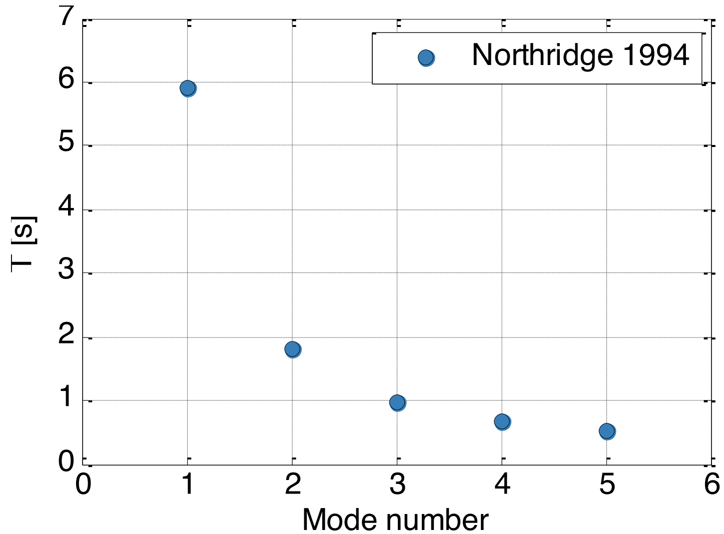
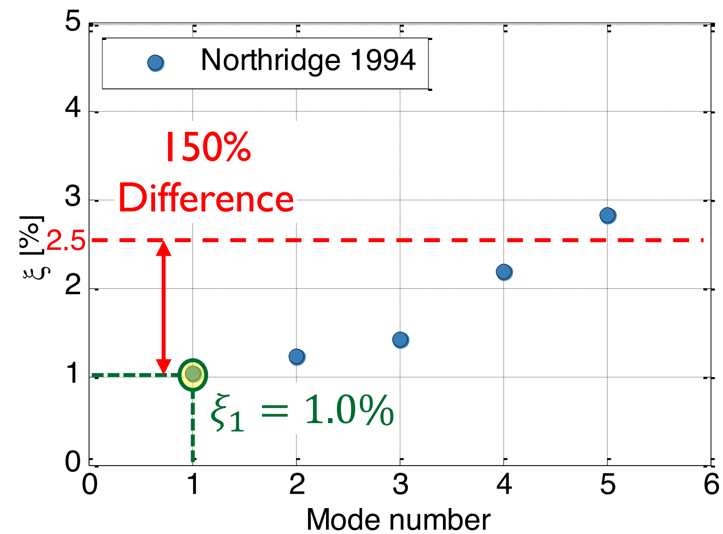
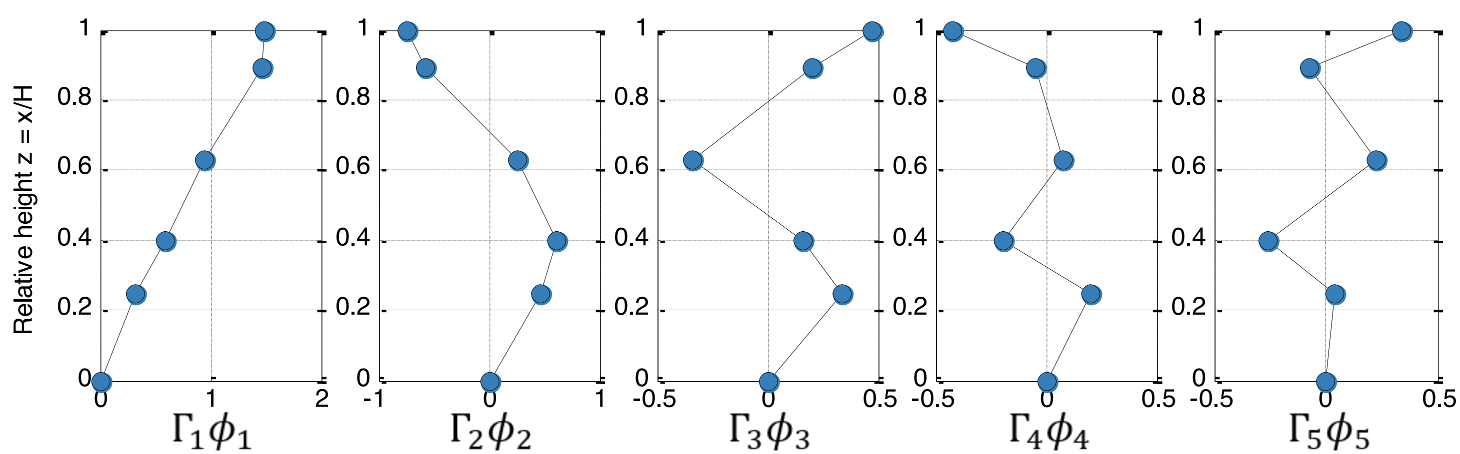
Example

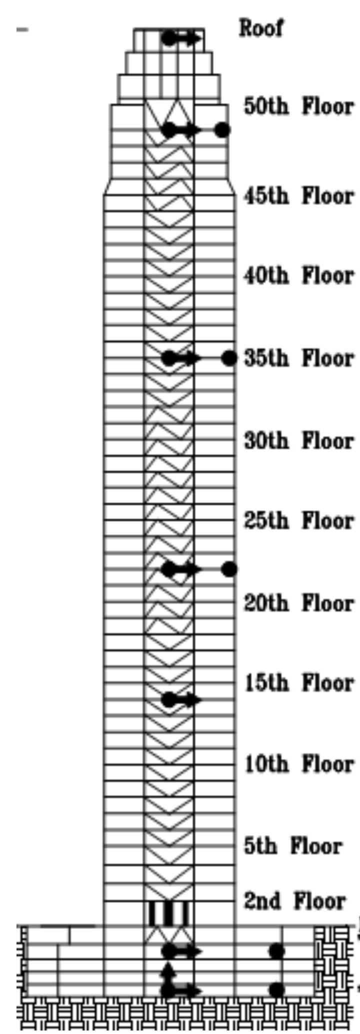
52-Story Office Building in downtown LA (NS Direction)

$$\theta = \left\{ \begin{pmatrix} T_1 \\ \vdots \\ T_{N_m} \end{pmatrix} ; \begin{pmatrix} \xi_1 \\ \vdots \\ \xi_{N_m} \end{pmatrix} ; \begin{bmatrix} \Gamma_1 \phi_1^1 & \cdots & \Gamma_{N_m} \phi_{N_m}^1 \\ \vdots & \ddots & \vdots \\ \Gamma_1 \phi_1^{N_{sen}} & \cdots & \Gamma_{N_m} \phi_{N_m}^{N_{sen}} \end{bmatrix} \right\}$$

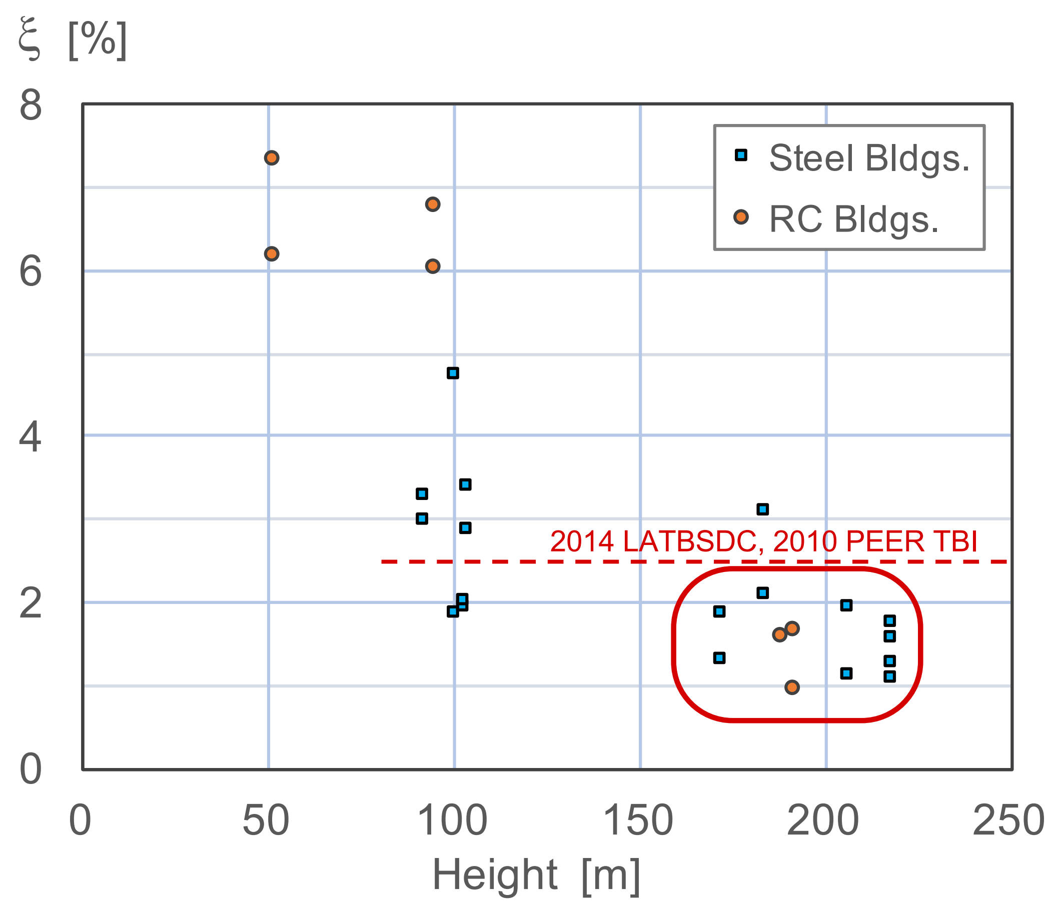








Results from 14 tall buildings



For buildings with heights larger than 150 m (490 ft) all inferred damping ratios are smaller than currently recommended values of 2.5% except for one building that has sloshing dampers in the transverse direction.

Complete dataset

PEER

Buildings analyzed

- Number of recorded seismic responses: 1335
- Total number of buildings: 154
- Total number of earthquakes: 117
- Total number of reliable data points : 1038

Comparison of size of dataset with what was used as basis for PEER's TBI v1.0

- ATC-72: 86
- This study: 1038

(After Cruz and Miranda; 2017, 2018)

Damping Ratio in the First Translational Mode

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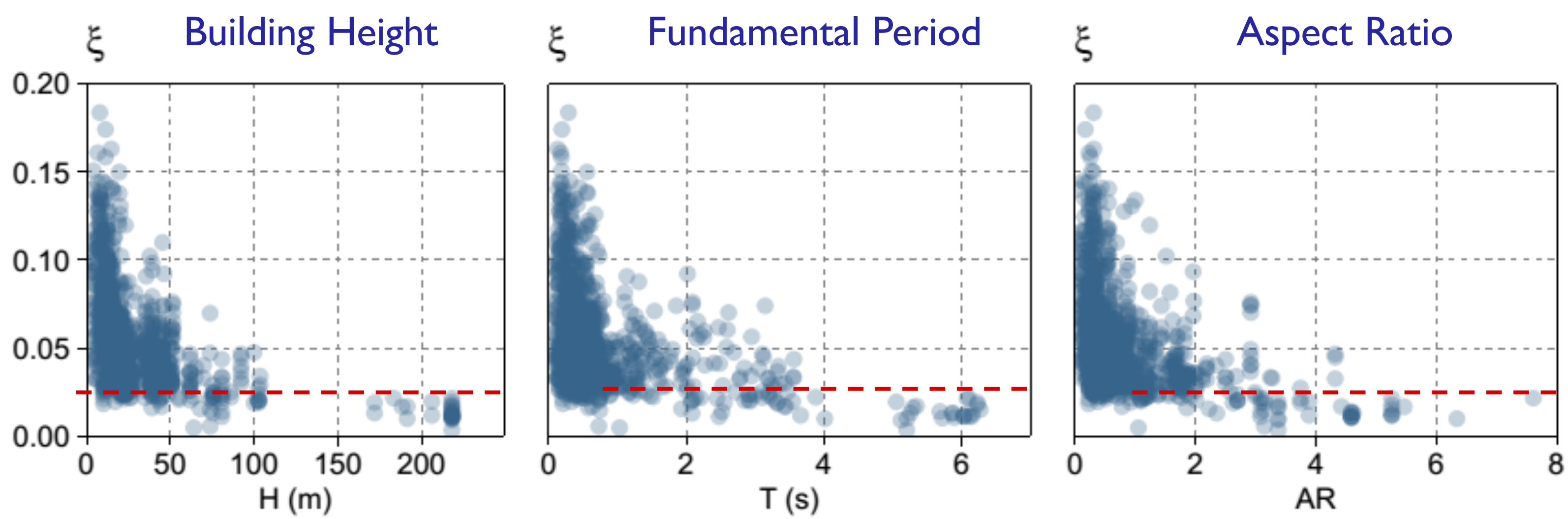
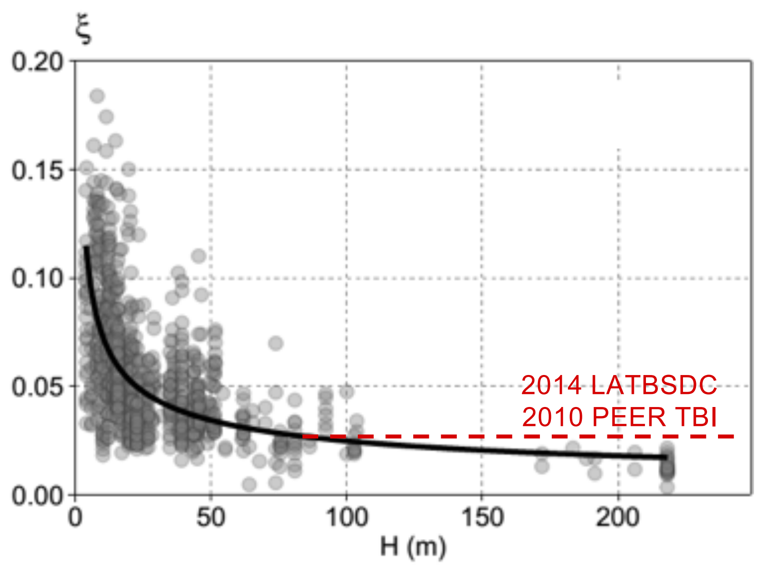
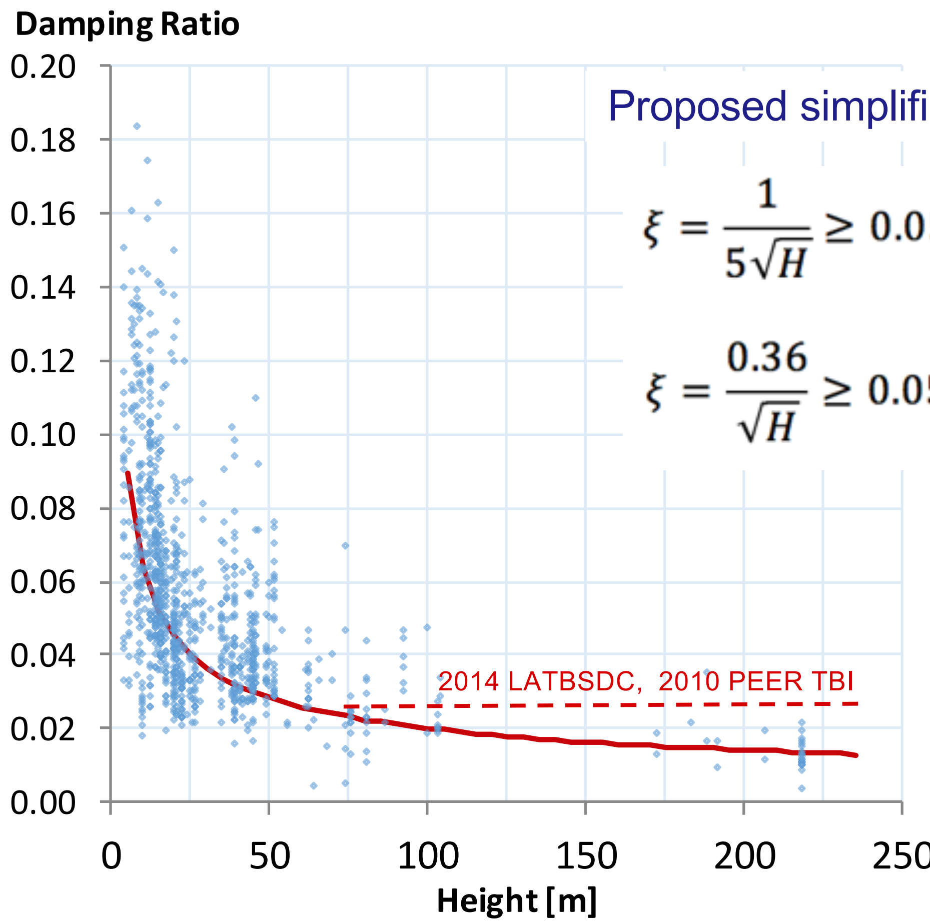
We have now expanded the study to more than 154 buildings most of which have recorded several earthquakes for more than 1,000 data points on damping ratios





E. Miranda & C. Cruz

Damping Ratio in the First Translational Mode

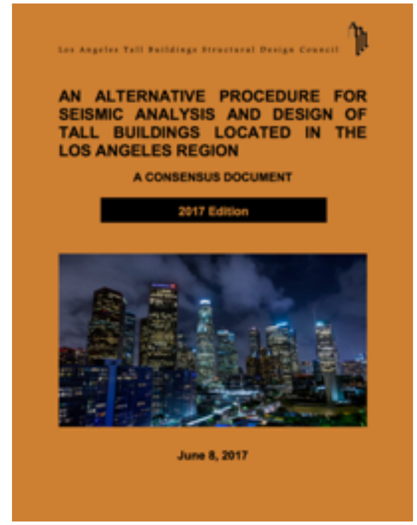


Proposed simplified equations:

$$\xi = \frac{1}{5\sqrt{H}} \geq 0.05 \qquad \textit{if H in m}$$

$$\xi = \frac{0.36}{\sqrt{H}} \geq 0.05 \qquad \textit{if H in ft}$$

Damping Ratio in the First Translational Mode



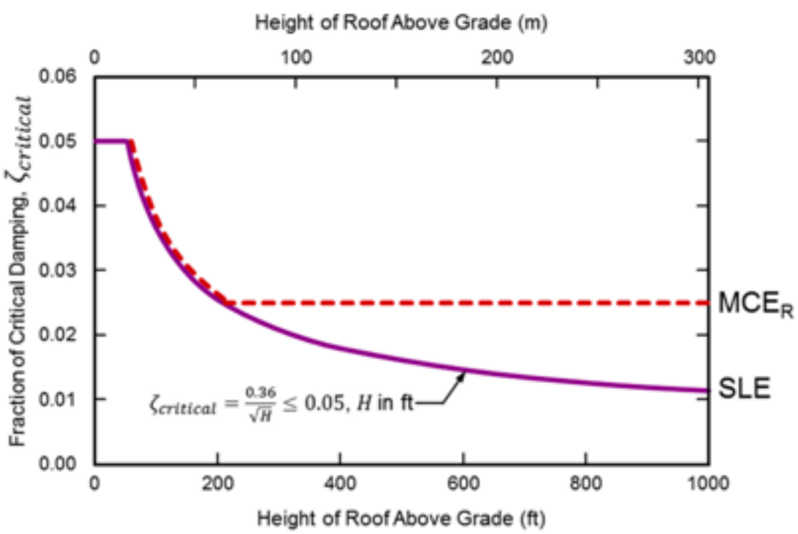


Figure 4-2 Equivalent viscous damping versus building height based on Equation (4-1).

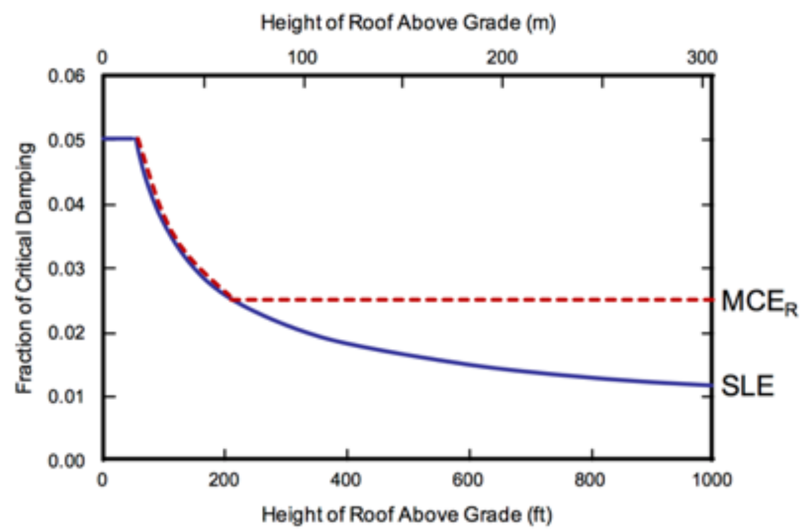
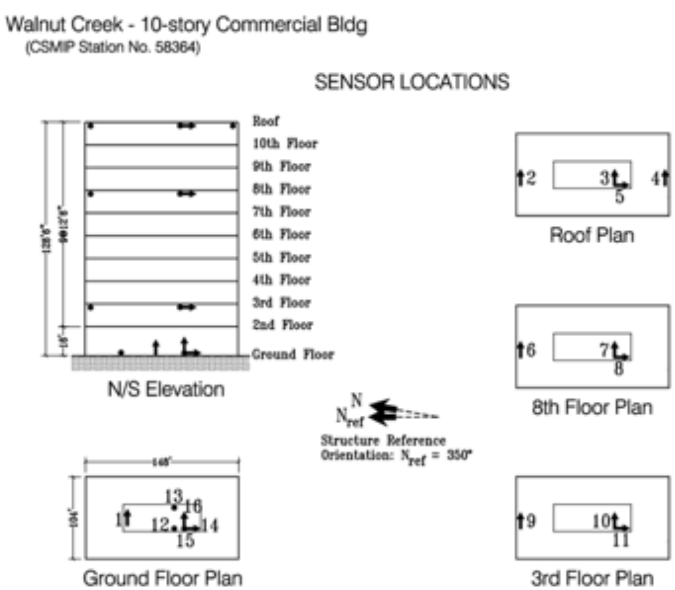


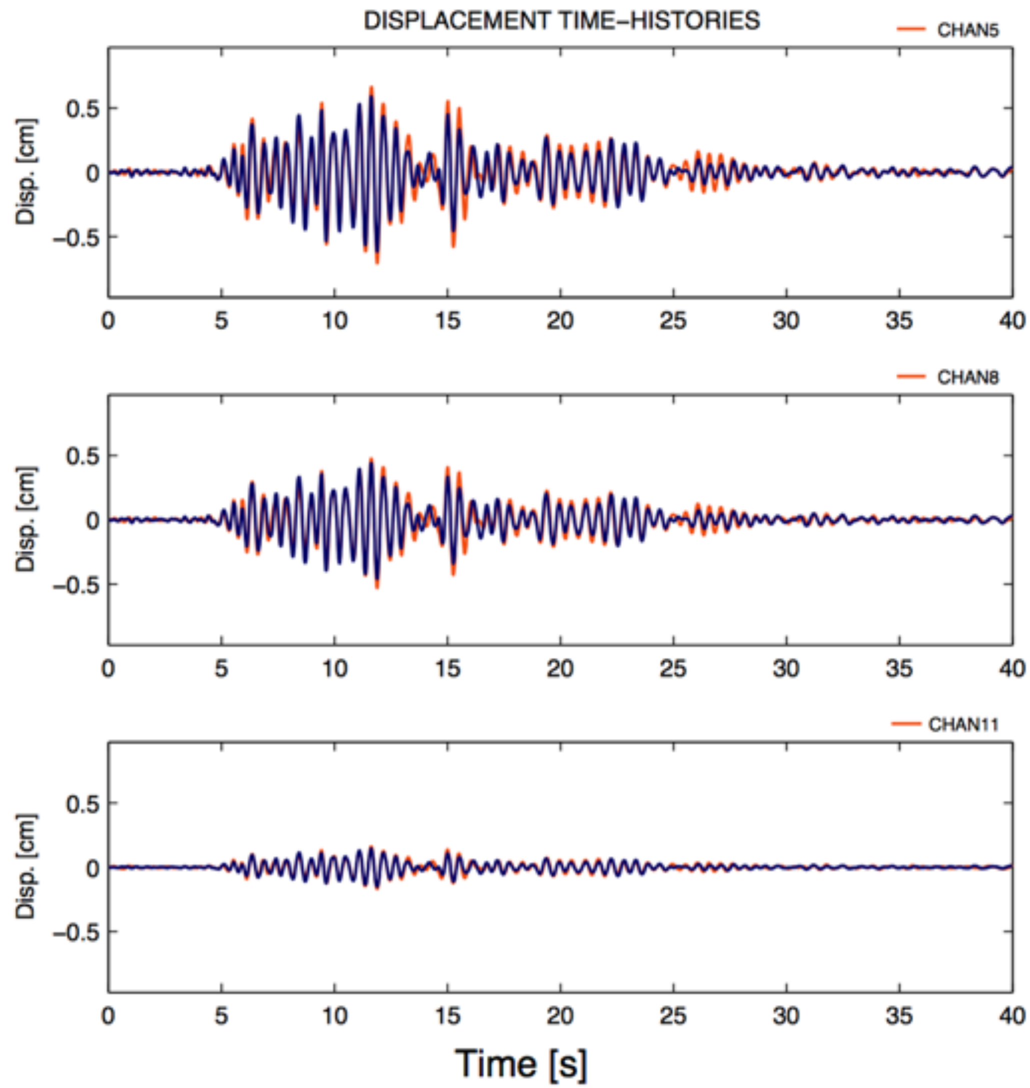
Figure 1. Equivalent viscous damping versus building height

Viscous ?

1980 Livermore Earthquake

(a) CSMIP 58364.





E. Miranda & C. Cruz

Evaluation of amplitude dependence

[redacted]

PEER

We have known for at least 50 years that damping ratio is amplitude dependent.

Damping in Percentage of Critical Damping

Test No.	Displacement Amplitude Ratio	Standard Method	Using Mode Shape	Hudson's Method
5a	1	1.16	1.24	1.44
5b	1.62	1.45	1.35	*
5c	1.97	1.48	1.39	1.51
8a	2.45	1.75**	1.49	1.88
8b	3.02	1.64	1.60	1.93
8c	0.79	1.54	1.47	1.74

INCREASING AMPLITUDE

*Only the response of the peak was measured, so it is not possible to apply this method.

Damping in Percentage of Critical Damping

Test No.	Displacement Amplitude Ratio	Standard Method	Using Mode Shape	Hudson's Method
10b	1.00	.69	.80	.97
10c	1.71	1.06	.89	.96
10d	2.74	1.12	.97	1.17
10e	3.44	1.12	1.01	1.15
10f	4.38	1.21	1.16	*
10g	5.08	1.48	1.20	1.50
10g†	5.20	1.70	1.16	1.46

INCREASING AMPLITUDE

*Only frequencies close to the peak were measured, so it is not possible to apply this method.

(After Kuroiwa and Jennings, 1979)

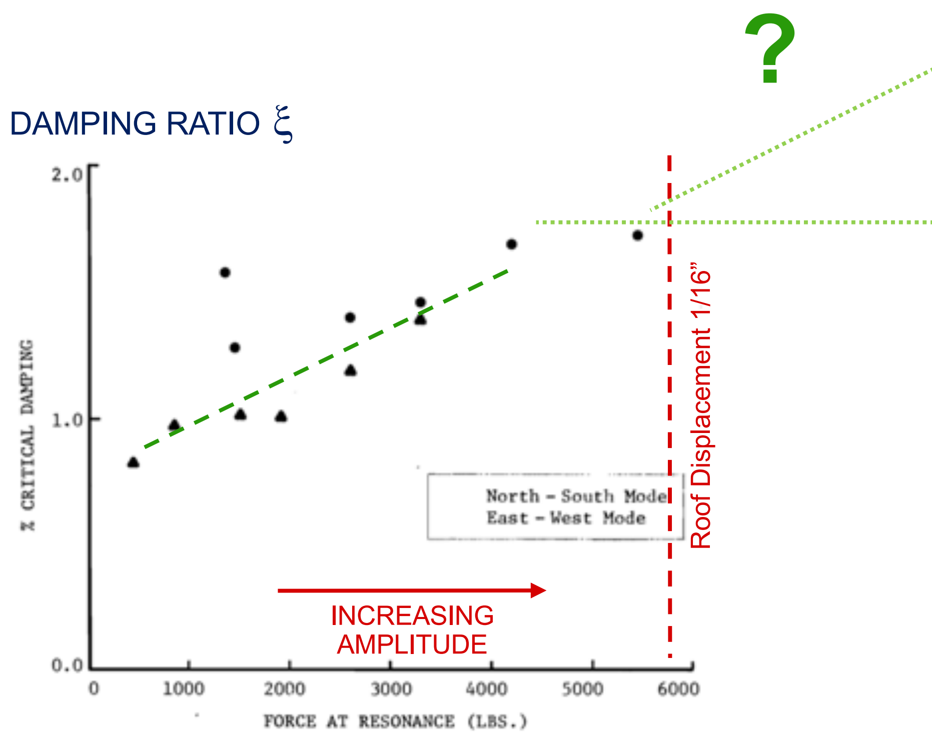


FIGURE 17

% CRITICAL DAMPING VS. FORCE AT RESONANCE

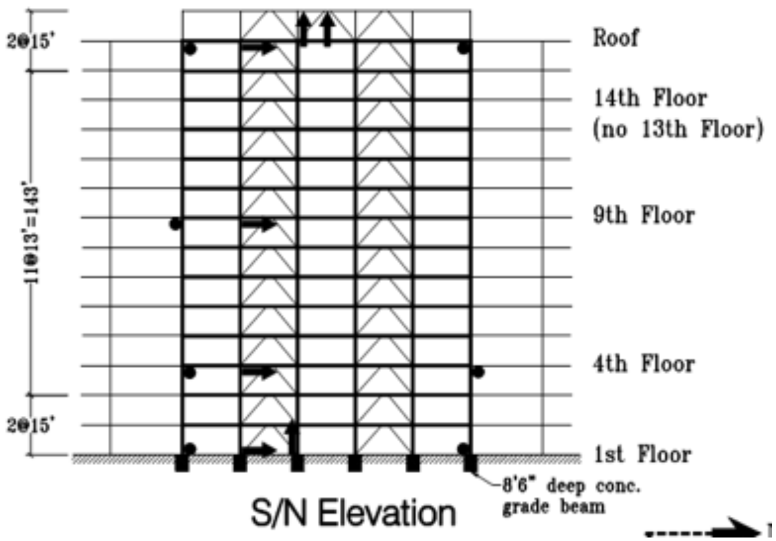
MILLIKAN LIBRARY BUILDING

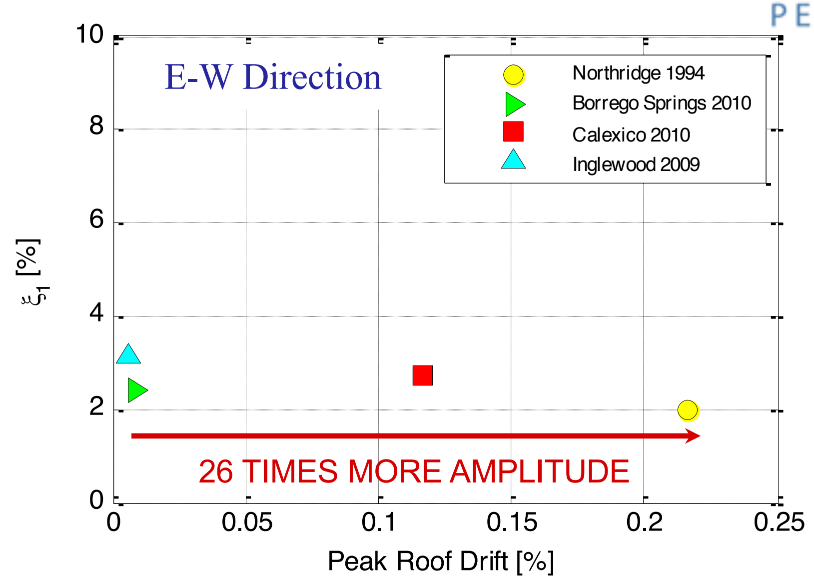
(Drawn from Data given in Reference 35)

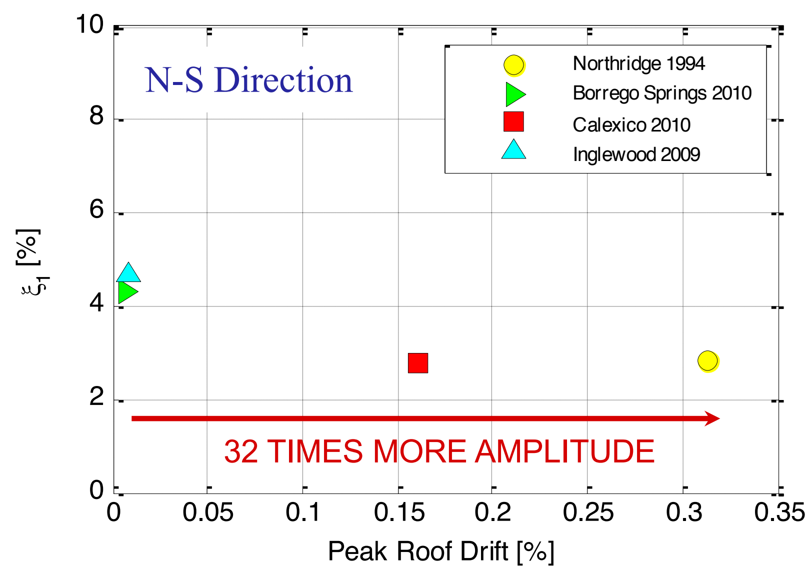
(After Haviland, 1979)

Evaluation of amplitude dependence

Is damping amplitude dependent?



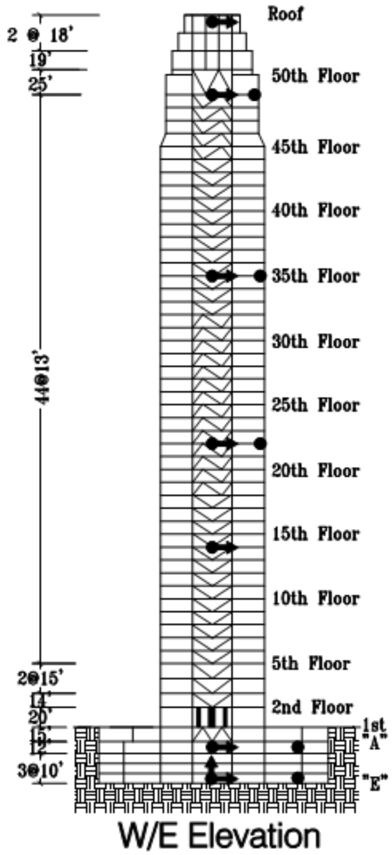


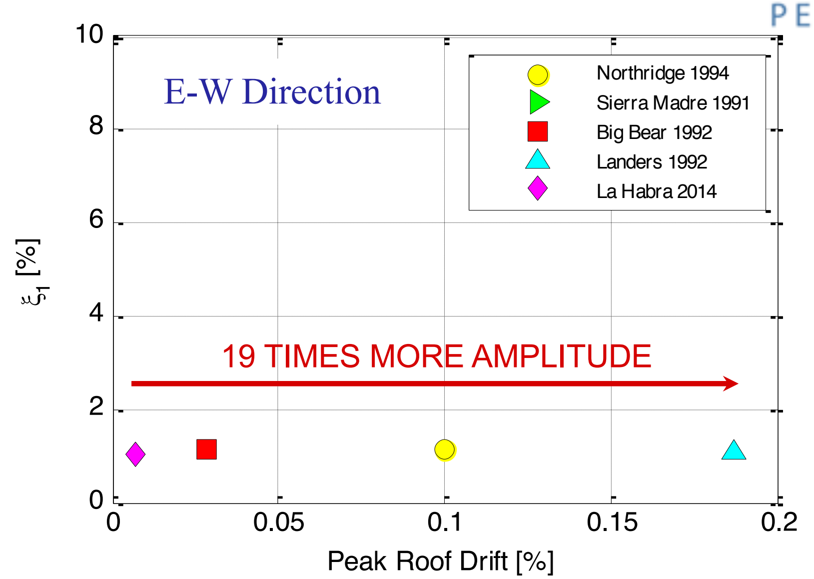


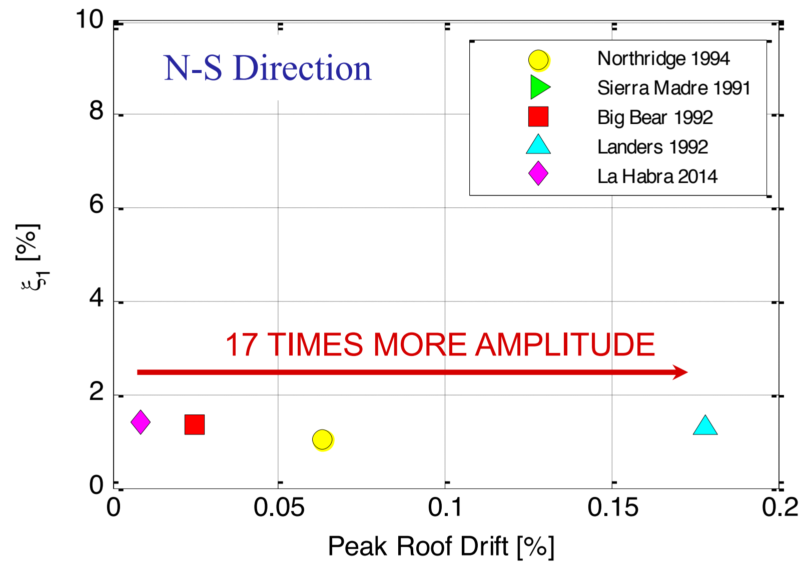
- El Segundo - 14S
- Showing results for the first mode only

Evaluation of amplitude dependence

Is damping amplitude dependent?



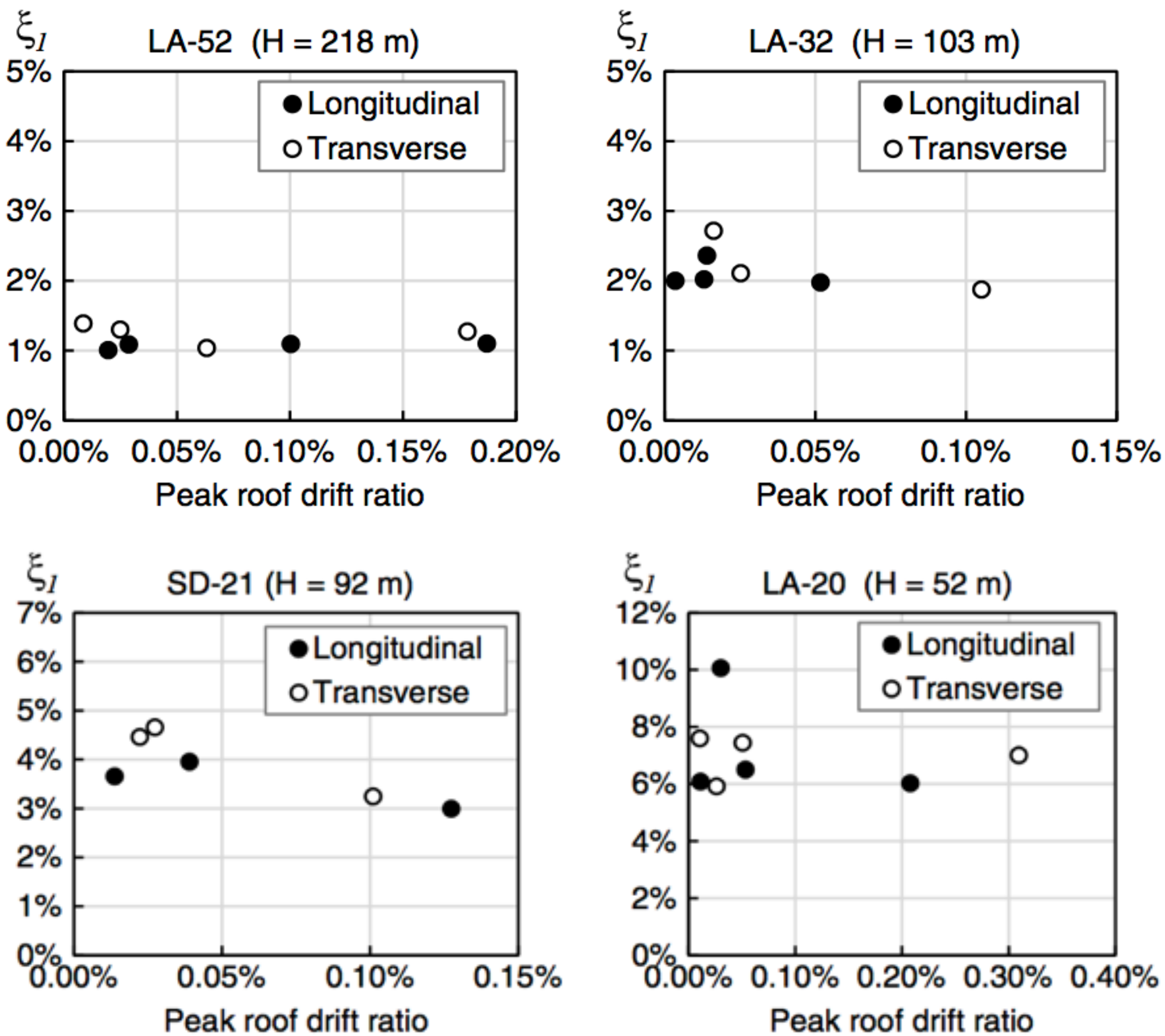




- Los Angeles - 52S
- Showing results for the first mode only

Evaluation of amplitude dependence

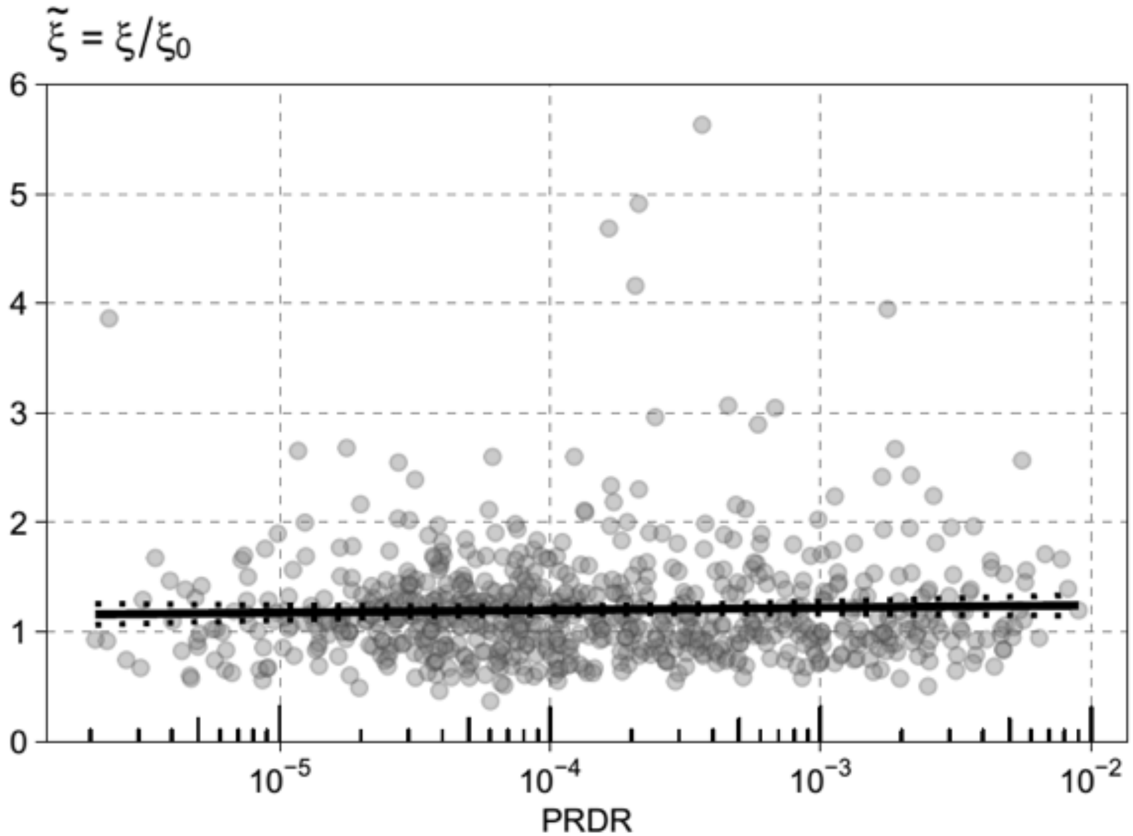
Is damping amplitude dependent?



(After Cruz and Miranda, 2016)

Evaluation of amplitude dependence

Is damping amplitude dependent?

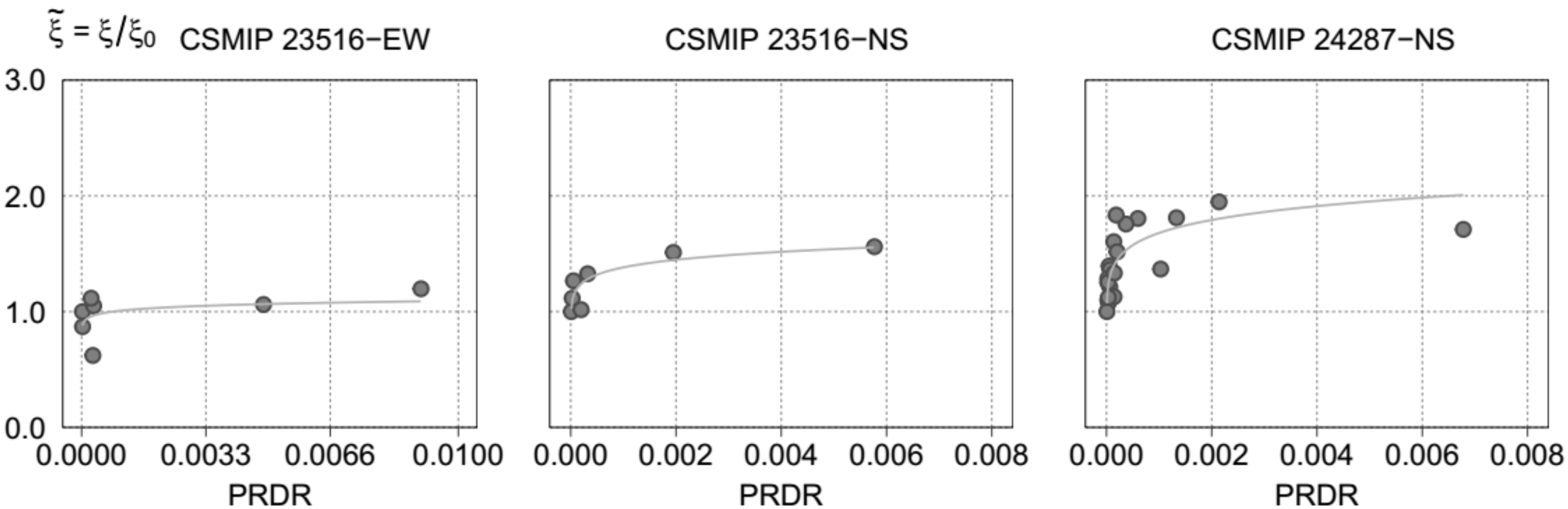


With exception of extremely small levels of deformation, practically no amplitude dependence was observed with changes in amplitude of x10, x30.

Evaluation of amplitude dependence

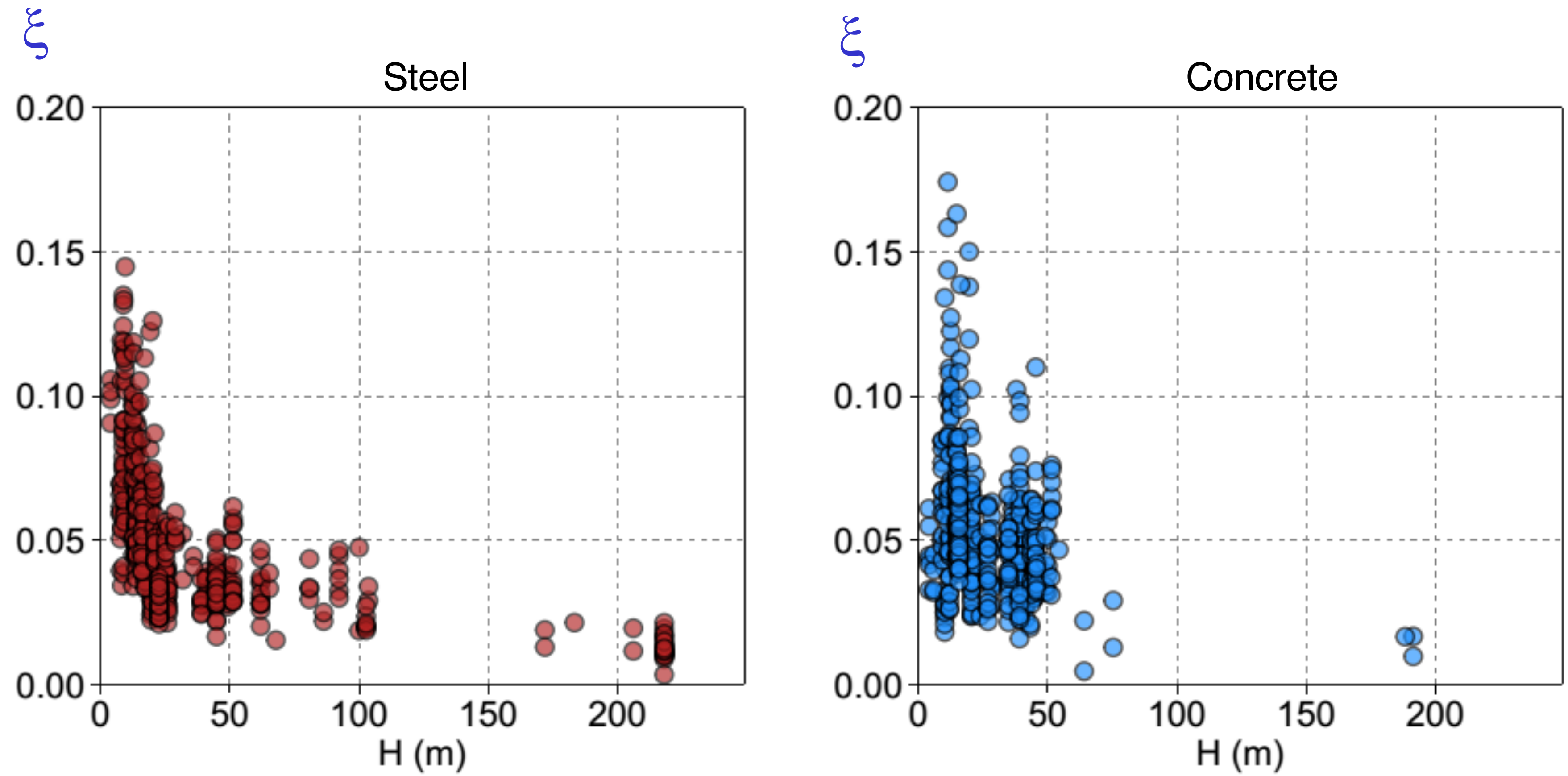
[redacted]

Is damping amplitude dependent?



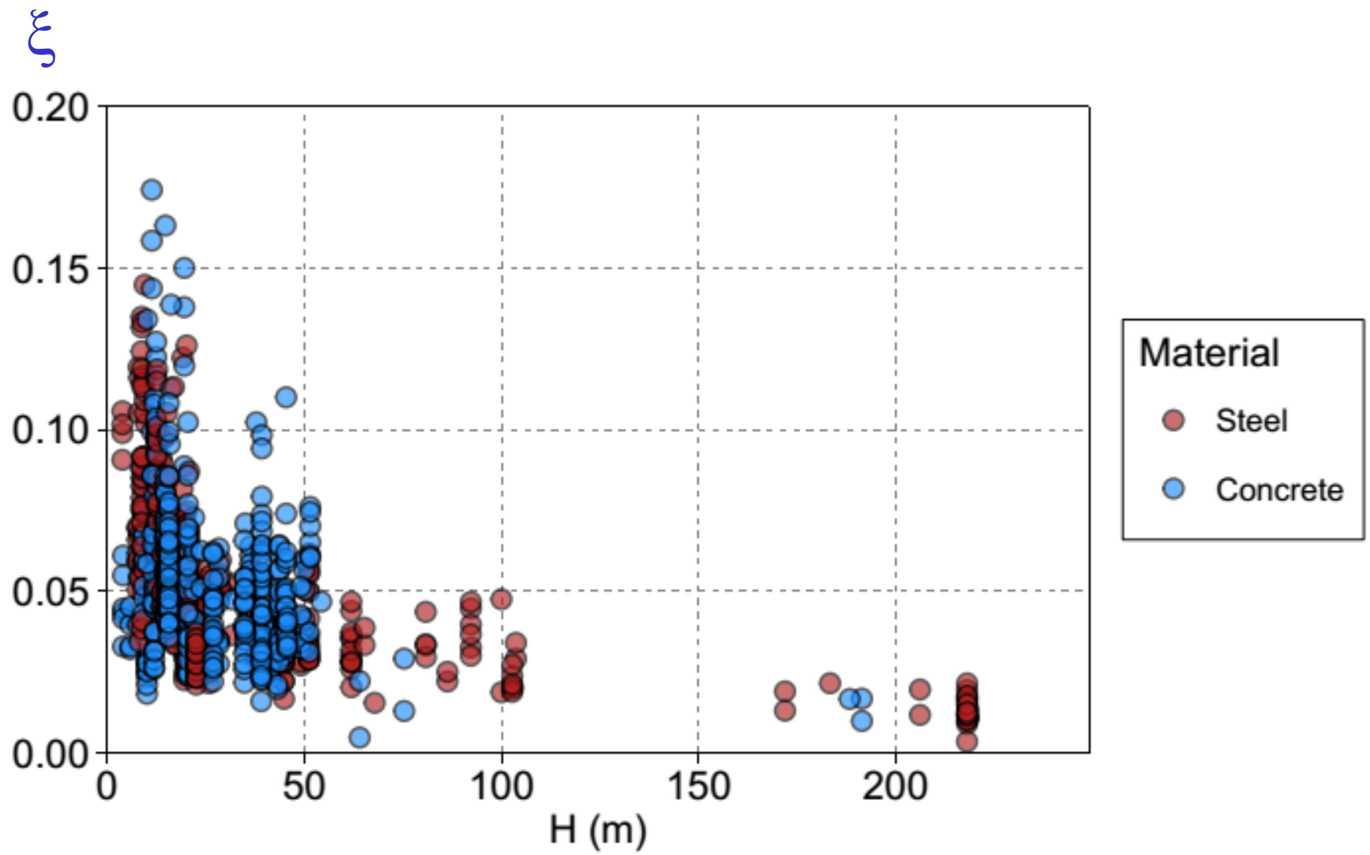
Influence of primary structural material

$$\xi_{steel} < \xi_{concrete} \textbf{ ?}$$



Influence of primary structural material

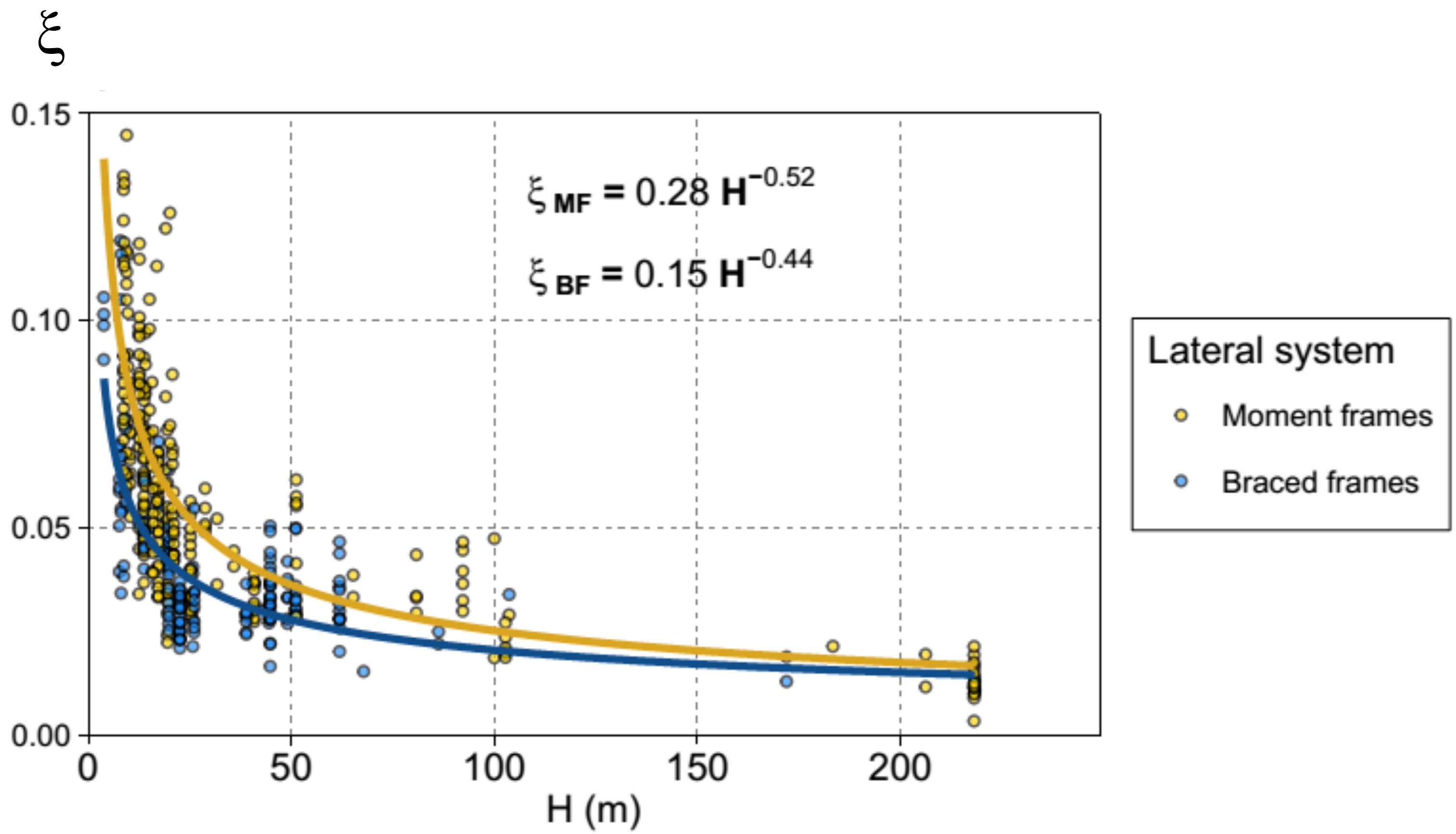
$$\xi_{steel} < \xi_{concrete} \ ?$$



There is no statistical difference between damping ratios in steel and reinforced concrete buildings.

How about the role of the lateral resisting system

$$\xi_{SMRFs} = \xi_{SBFs} \ ?$$



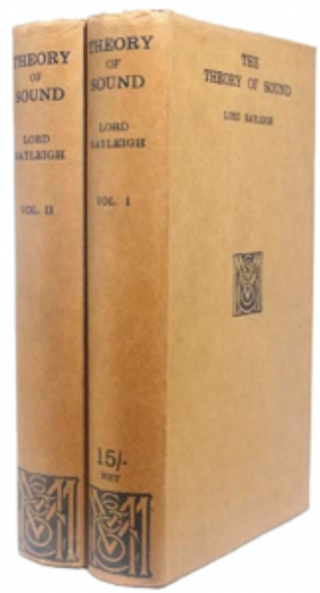
This observation is consistent with previous observations with wind loading by Prof. Kiewisky-Correa at ND.

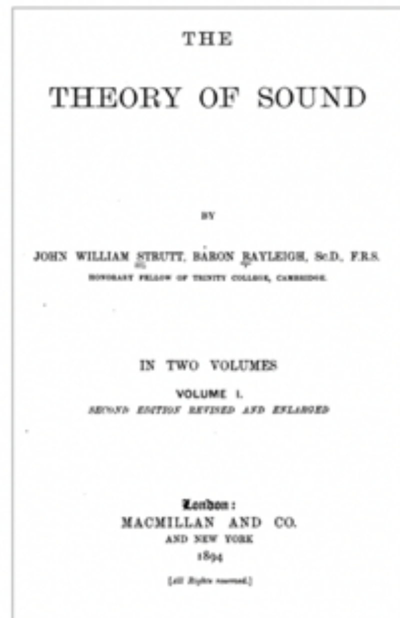
Is Rayleigh Damping really a good model ?

- Originally proposed by John W. Strutt (Lord Rayleigh) in 1877
- Damping matrix proportional to [M], [K] or a linear combination of these two that allows uncoupling the equations of motion
- Most commonly used damping model

John William Strutt,
Baron of Rayleigh
(Lord Rayleigh)

Nobel prize in physics 1904





THE

THEORY OF SOUND

BY

JOHN WILLIAM STRUTT, BARON RAYLEIGH, Sc.D., F.R.S.
HONORARY FELLOW OF TRINITY COLLEGE, CAMBRIDGE.

IN TWO VOLUMES

VOLUME I.

SECOND EDITION REVISED AND ENLARGED

London:
MACMILLAN AND CO.
AND NEW YORK
1894

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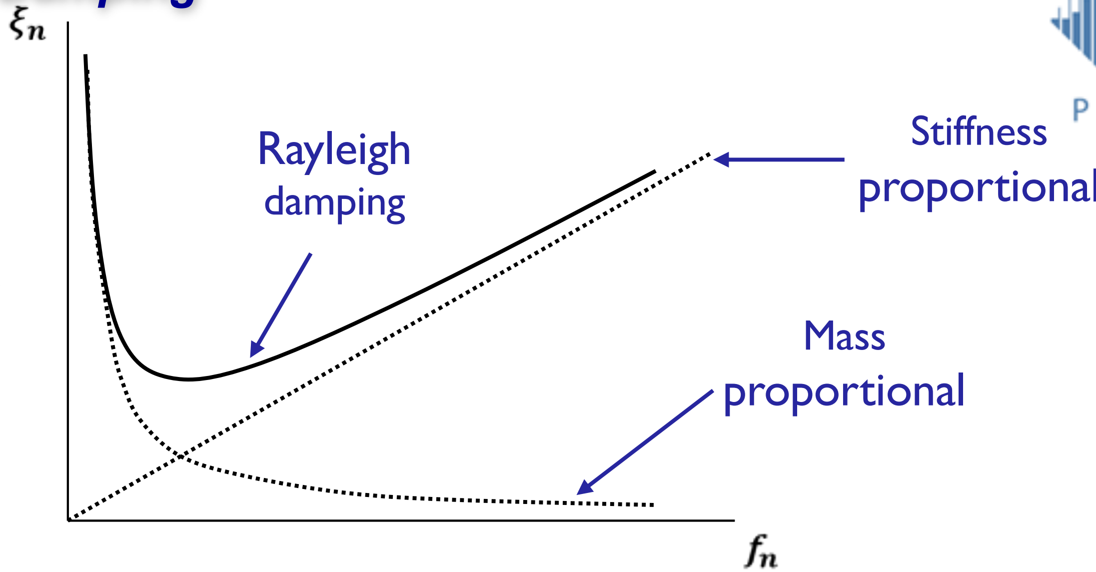
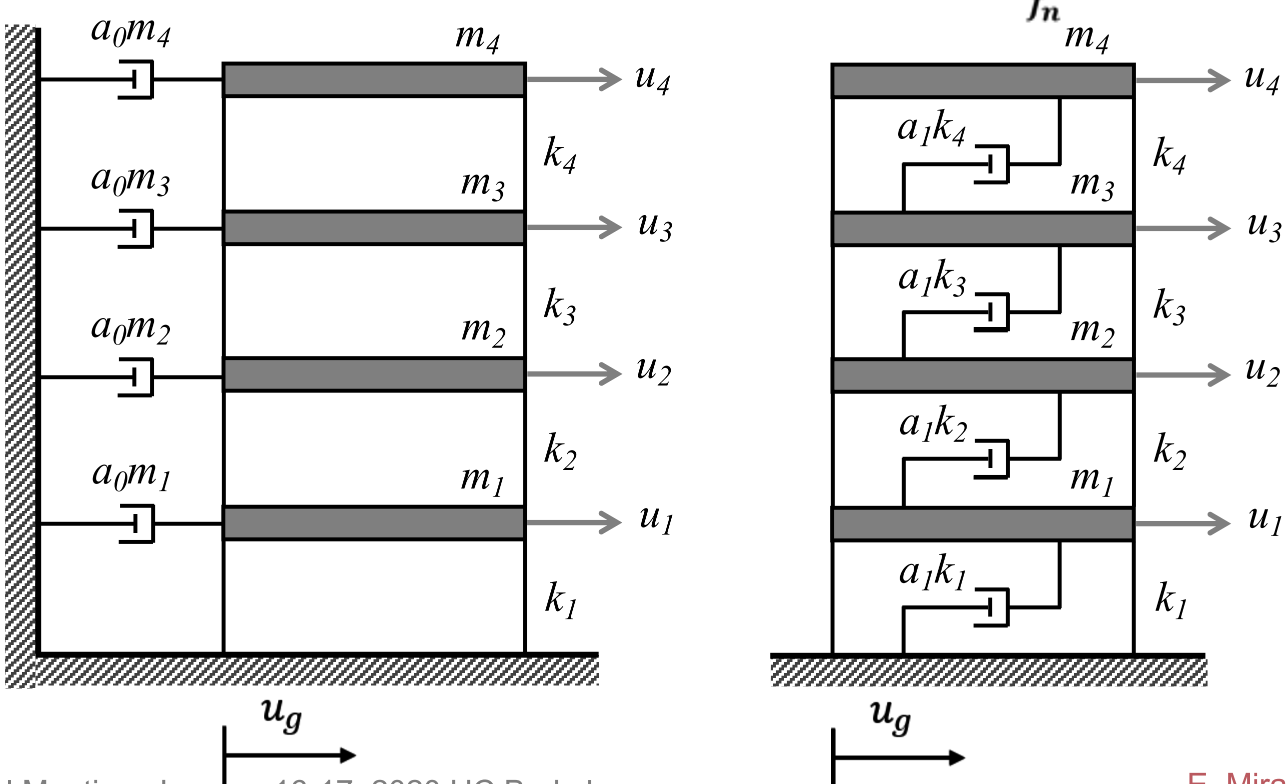
First published in 1877

BUT IS IT REALISTIC OR ADEQUATE ?

Evaluation of Rayleigh Damping

$$[C] = a_0[M] + a_1[K]$$

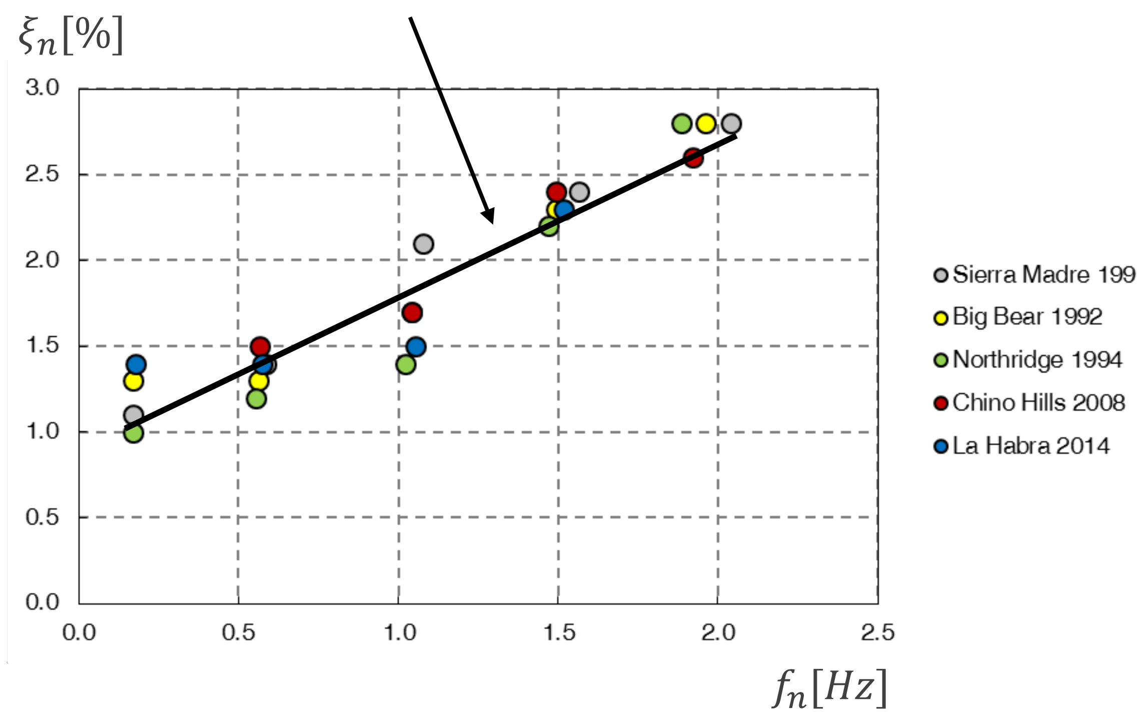


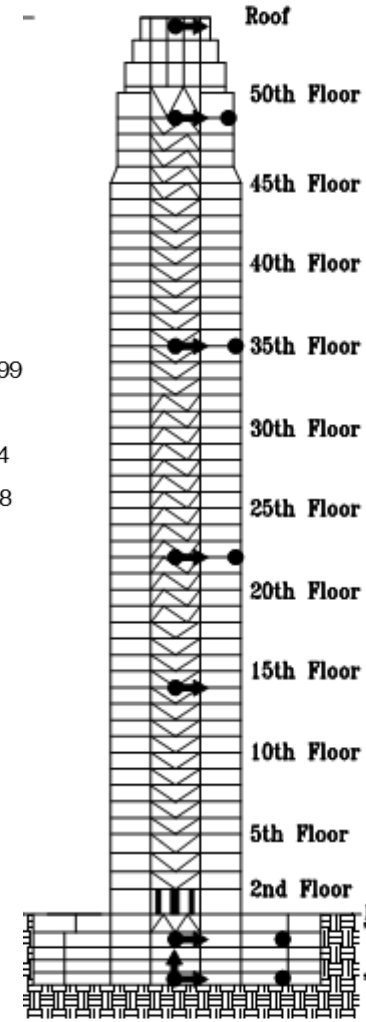


Damping Ratio as a Function of Frequency

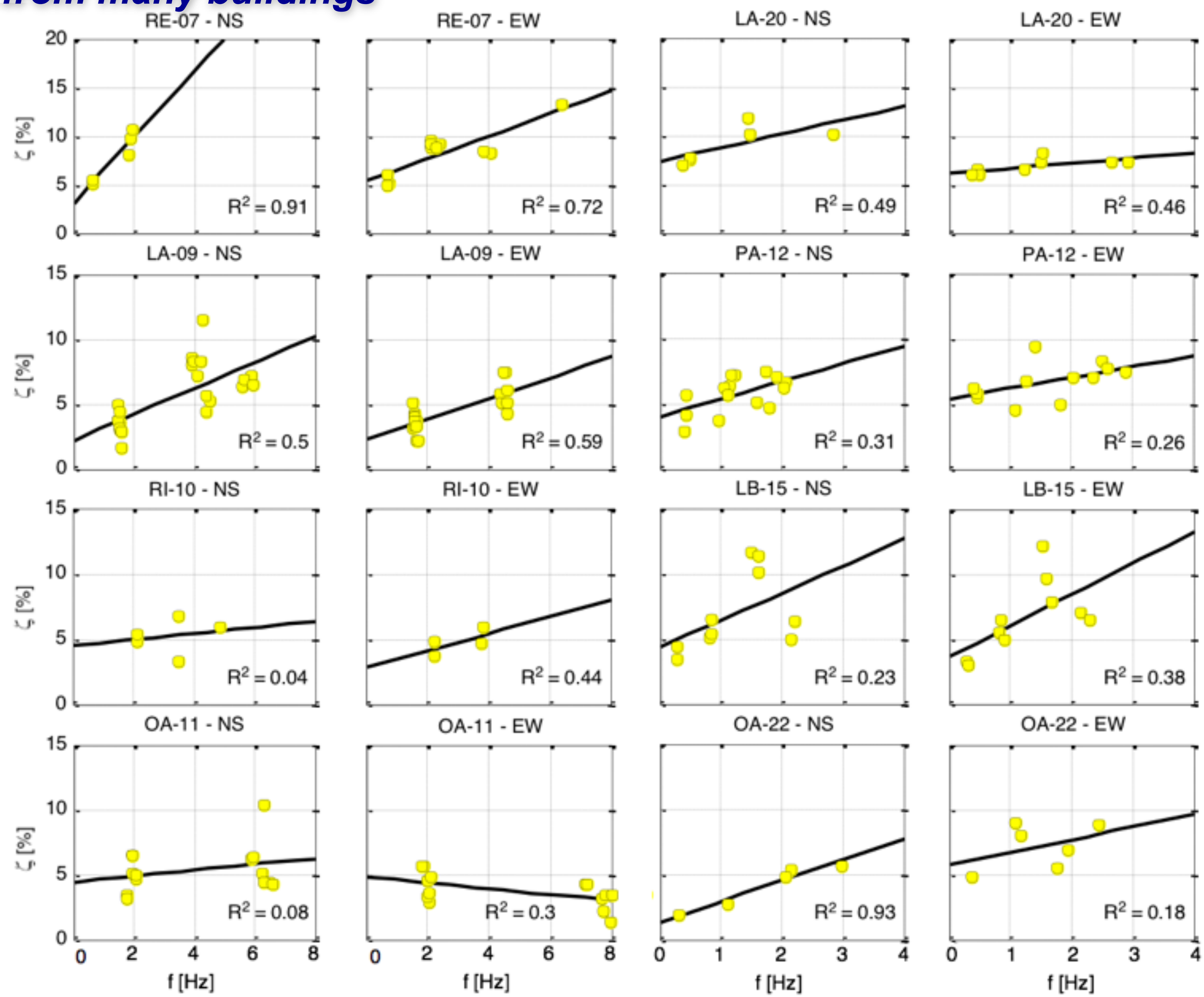
52-Story Office Building in downtown LA (NS Direction)

$$\xi_n(f) = \xi_0 + \beta f_n$$



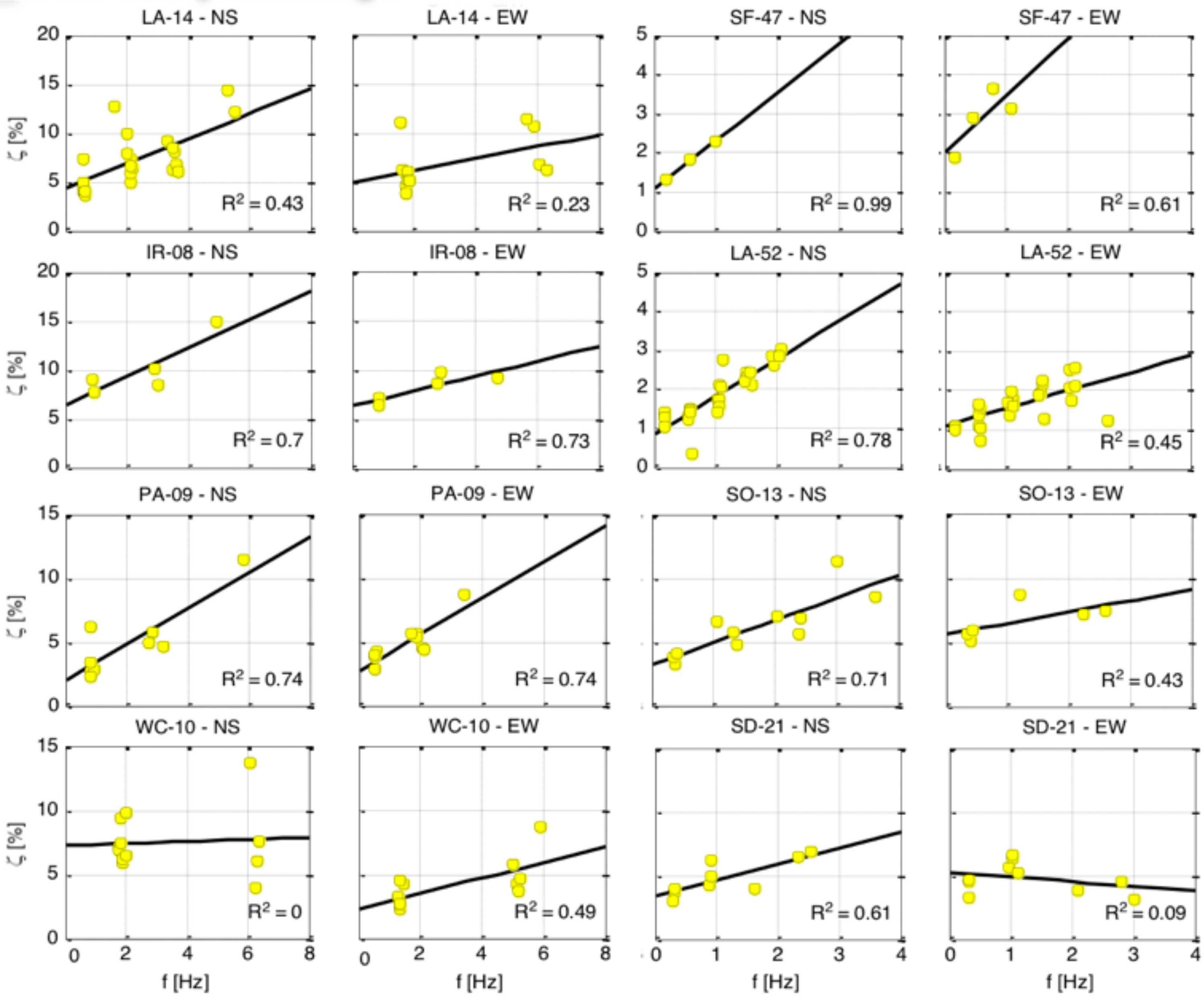


Results from many buildings



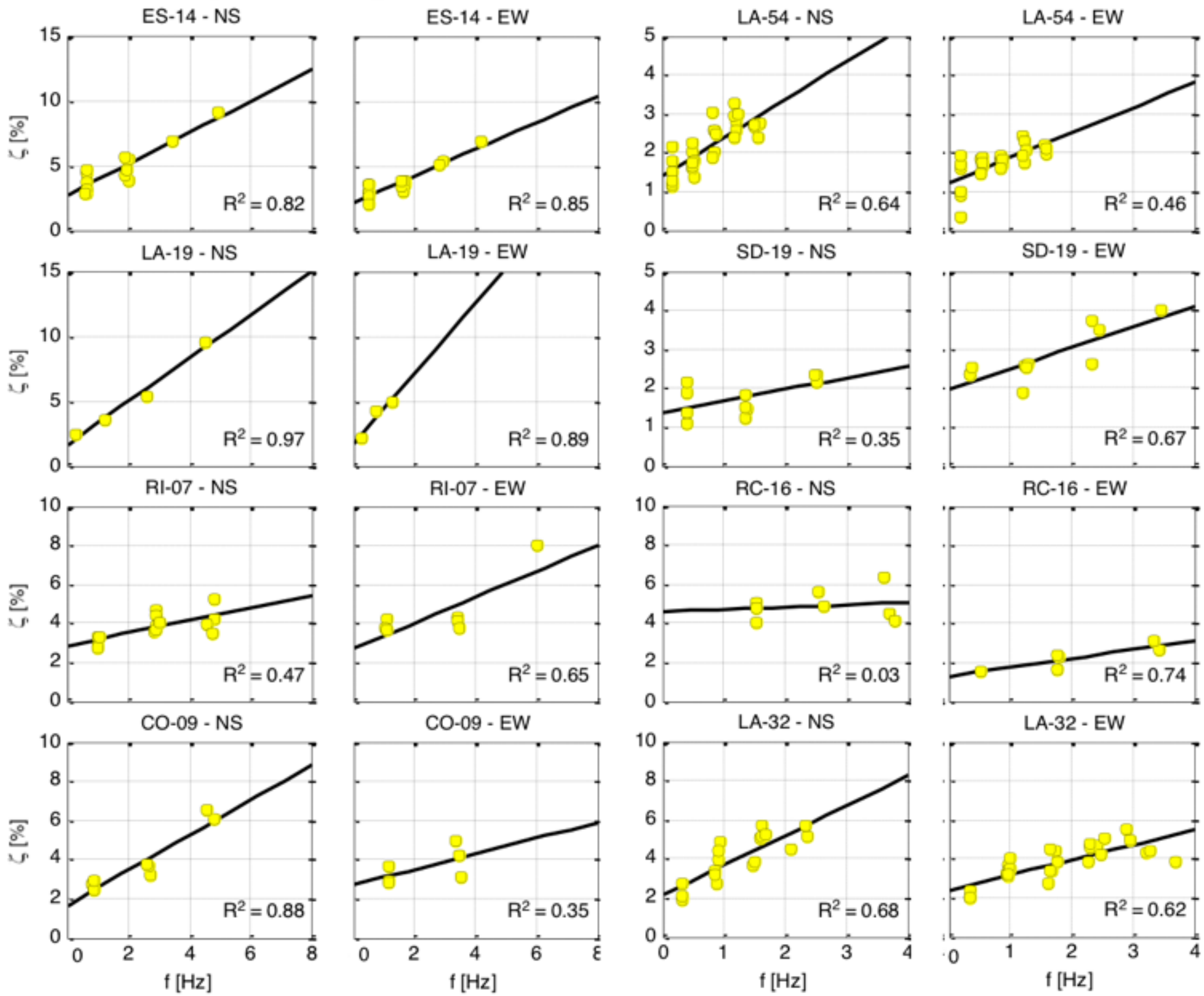
(After Cruz and Miranda, 2017)

Results from many buildings



(After Cruz and Miranda, 2017)

Results from many buildings



(After Cruz and Miranda, 2017)

Summary and Conclusions

- Damping ratios decrease with increasing building height;
- Consistent with wind loading studies, once we exceed a very small level of lateral deformation, we don't see much (any?) amplitude-dependent damping.
- Primary structural material (e.g. steel vs RC) does not show any statistical significant difference but lateral resisting system in some cases lead to different damping ratios;
- The damping ratios we are obtaining are very similar to those reported in the wind literature for large amplitude wind loading;
- Damping ratios increase linearly with frequency and this applies to both the fundamental modes and higher modes, but its not quite a stiffness proportional damping;
- No evidence of mass-proportional damping was found, so we do not recommend the use of Rayleigh damping;
- **SSI plays a major role in understanding damping ratios in buildings**, in particular radiation damping, explains:
    1. Why viscous damping works very well
       (this is consistent with Lysmer & Kuhlemeyer, 1969);
    2. Reduction of damping ratio with increasing height (or T1 or H/R);
    3. Increase in damping ratio with increasing frequency

Our next test bed…