Do Scaled Ground Motion Records Cause Biased Nonlinear Structural Responses?





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www.air-worldwide.com

Problem Statement

Given:

1) A nonlinear structural model to be dynamically analyzed (design or evaluation) at a specific site.

2) A grc

3) An ea ance (R),
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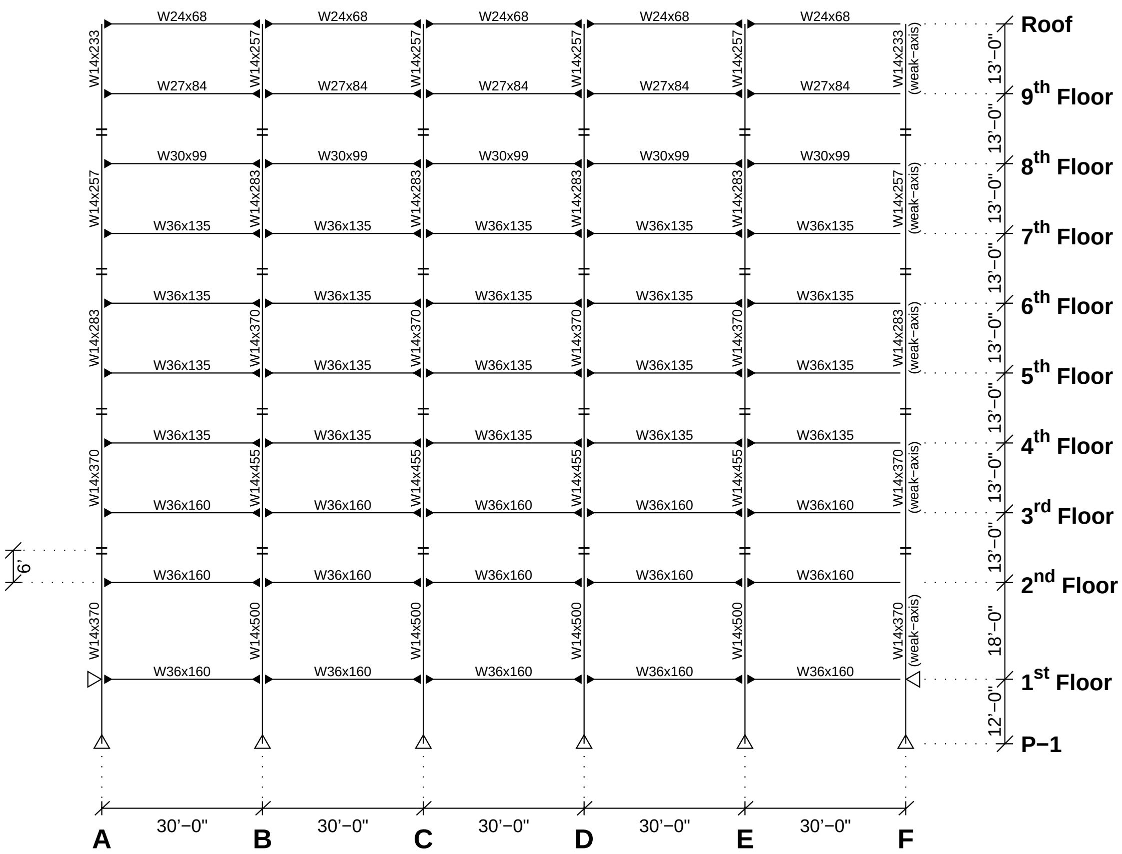
e.g., .



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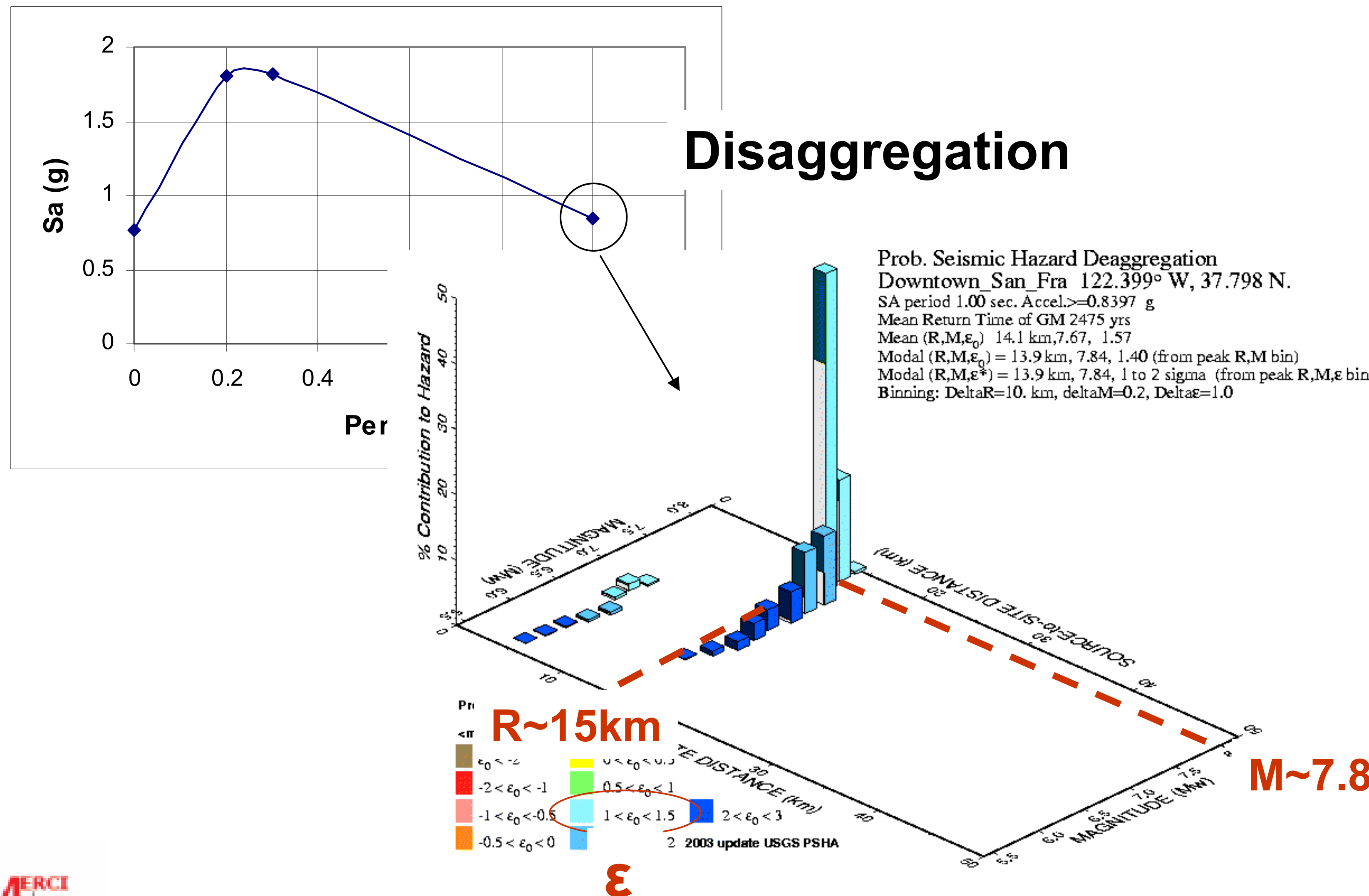
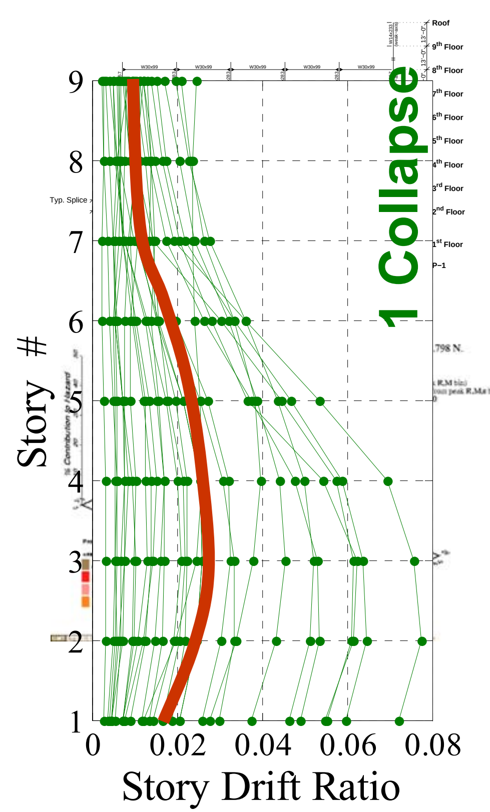
Possible Genesis of a Target Response Spectrum

2%/50yr Uniform Hazard Spectrum for San Francisco



Problem Statement (cont'd)



<u>Given:</u>

1) A nonlinear structural model to be dynamically analyzed.

2) An earthquake magnitude (M), source-to-site distance (R), and $S_a(T_1)$ level

<u>Find:</u>

➢ The "average" (geometric mean) nonlinear structural response for the target ground motion.

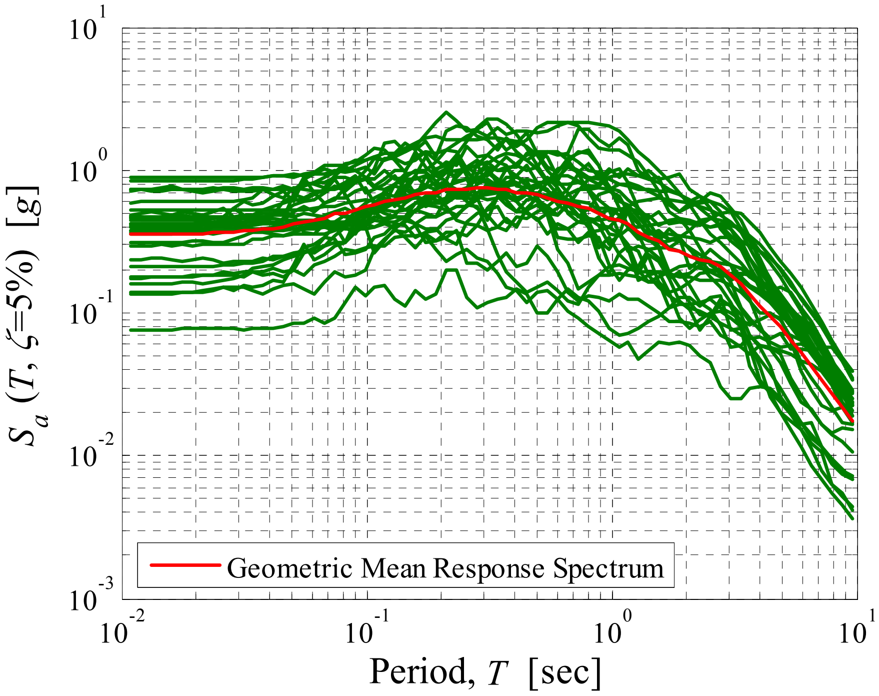
e.g., story drift ratios ≡ differential horizontal displ. of floors

Availability of Ground Motion Records of given M, R, $S_a(T_1)$

- Next Generation Attenuation (NGA) Project has about 3,500 "uniformly" processed three-component recordings

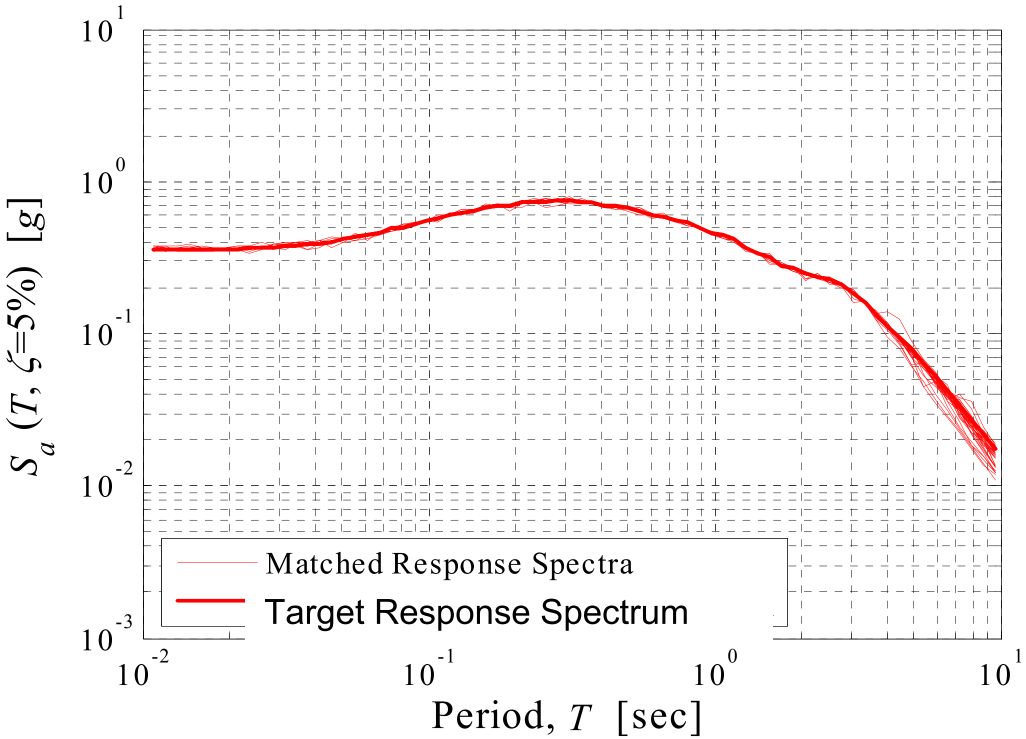
- In many practical applications:
  - M large
  - R is short
  - $S_a(T_1)$ is high

- "Right" records are <u>**scarce**</u>



Alternative No 1: Spectrum matching

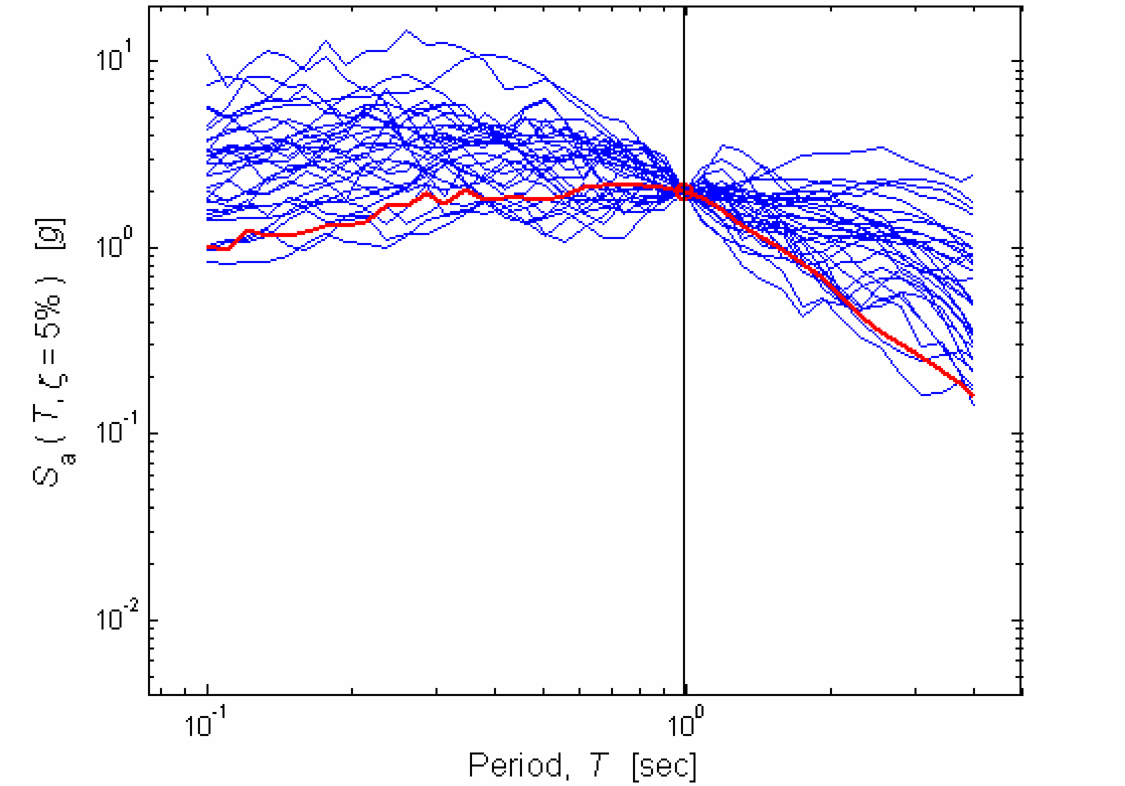
- Spectrum match earthquake records to "appropriate" target spectrum of given M, R, and $S_a(T_1)$, *e.g.*,



- Perform nonlinear dynamic analyses and calculate the geometric mean response

Alternative No 2: Amplitude Scaling

- Scale (in amplitude only) the earthquake records to $S_a(T_1)$, e.g., when T_1 = 1.0 sec.,



- Perform nonlinear dynamic analyses and calculate the geometric mean response

Use of Scaled Records for NL Dynamic Analyses

- Is that a legitimate operation or does it introduce bias in <u>median</u> and dispersion of the structural response?

$$\text{Bias} = \frac{\text{median structural response to scaled records}}{\text{median structural response to unscaled records naturally at target } S_a}$$

- If there is a bias, does it depend
  - Scale factor
  - characteristics of the <u>target</u> ground motion scenario (e.g., *M* and *R*),
  - characteristics of the <u>source</u> records
  - vibration period(s) of the structure of interest
  - strength of the structure (i.e., level of response nonlinearity)
  - contribution of higher (than the first) vibration modes to the structural response.

- Are there records that are better candidate than others for scaling?

Analyses Setup: Bins of Ground Motion Records

- Intra-bin Scaling: "right" M and R but "wrong" (i.e., lower) $S_a(T_1)$ level

Bin Label	M_w	R_{close}
I	6.4 to 6.8	0 to 15km
II	6.4 to 6.8	15 to 30km
III	6.4 to 6.8	30 to 50km
IV	6.9 to 7.6	0 to 15km
V	6.9 to 7.6	15 to 30km
VI	6.9 to 7.6	30 to 50km

73 records each

+ Near Source Bin: as Bin I but forward directivity and orthogonal component. **31 records**

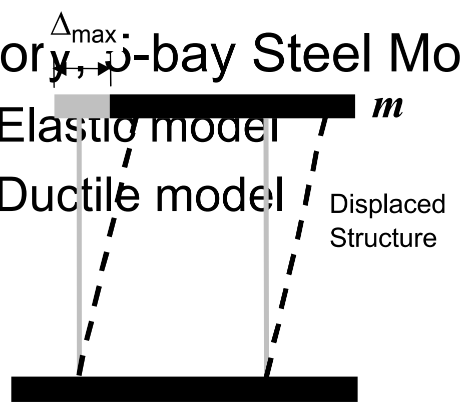
- Inter-bin Scaling: "wrong" M, and/or R, and/or $S_a(T_1)$ level

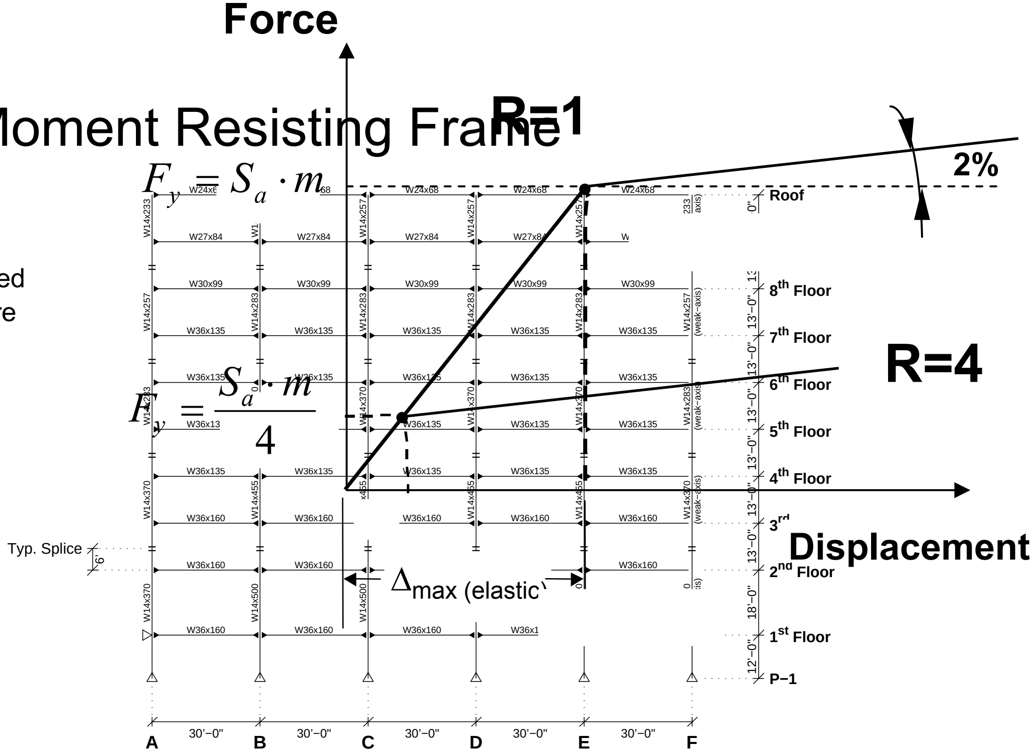
Scenario #	Source Bin	Target Bin
1	I	IV
2	II	IV
3	V	IV
4	II	V
5	III	V
6	VI	V
7	III	VI
8	III	I
9	I	Near-Source
10	Near-Source	I

Analyses Setup: Structures Considered

- 48 Single-Degree-of-Freedom (SDOF) NL Oscillators
  - 8 Periods: T = 0.1, 0.2, 0.3, 0.5, 1, 2, 3, and 4s.
  - 6 Strength Reduction Factors: R=1, 2, 4, 6, 8, and 10
  - Force-displacement hysteretic behavior is bilinear with 2% hardening (no strength or stiffness degradation)

- 9-story, 5-bay Steel Moment Resisting Frame
  - Elastic model
  - Ductile model





Measures of Structural Response

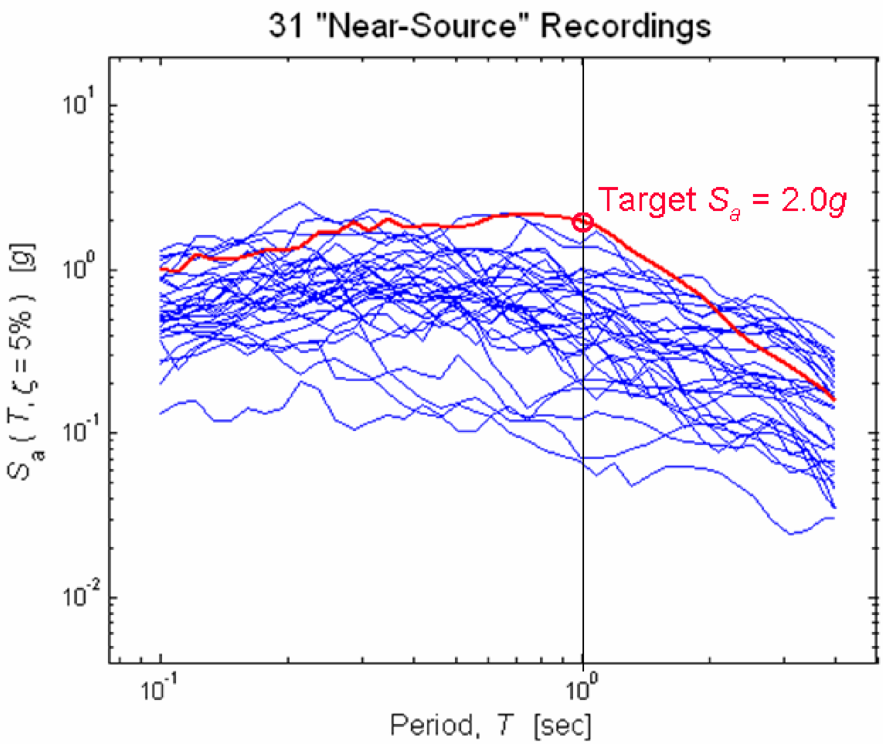
- SDOF systems: peak inelastic displacement (inelastic spectral displacement), S_d^i

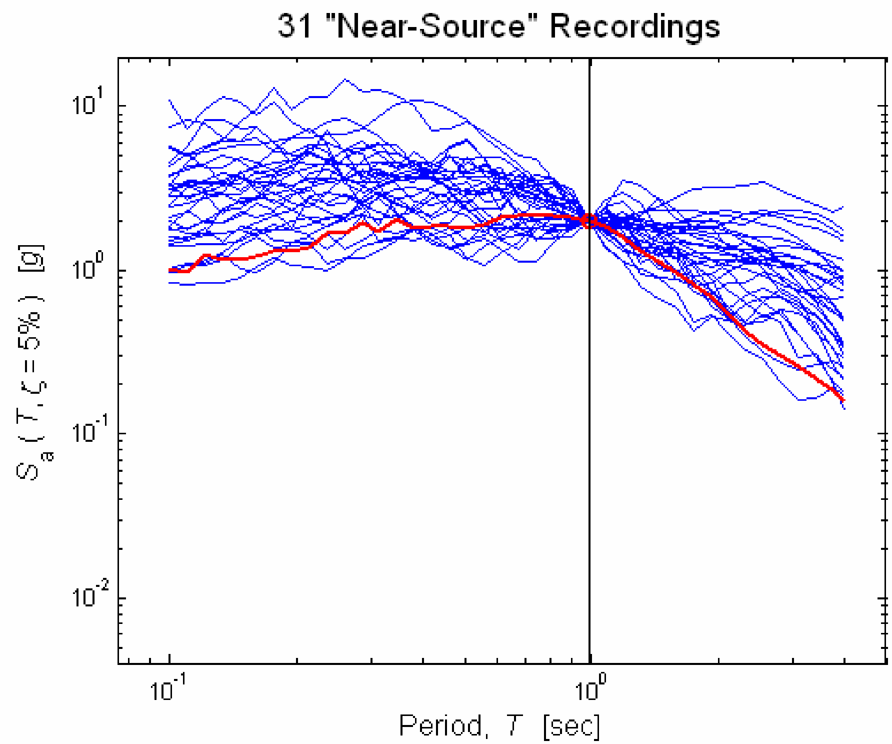
- MDOF Building (T_1=2.3s, υ_1=**2**% of critical):
  - the peak roof drift ratio, θ_{roof} (i.e., peak roof displacement normalized by the building height),
  - the maximum peak (over time) inter-story drift ratio over all stories, θ_{max}

- NOTES:
  - SDOF results are for constant R (yield strength varies from record to record). About 2M runs
  - MDOF results are for a fixed strength (about 6,500 runs)

Procedure for Quantifying Bias due to Scaling

- Select first target S_a for scaling and compute response
- Scale all other records in the "source" bin to the target S_a and keep track of scaling factor, SF, values





NOTE: results shown are for <u>intra bin</u> scaling: Near Source Record Bin, Moderate Strength (R=4) and Period (T=1s)

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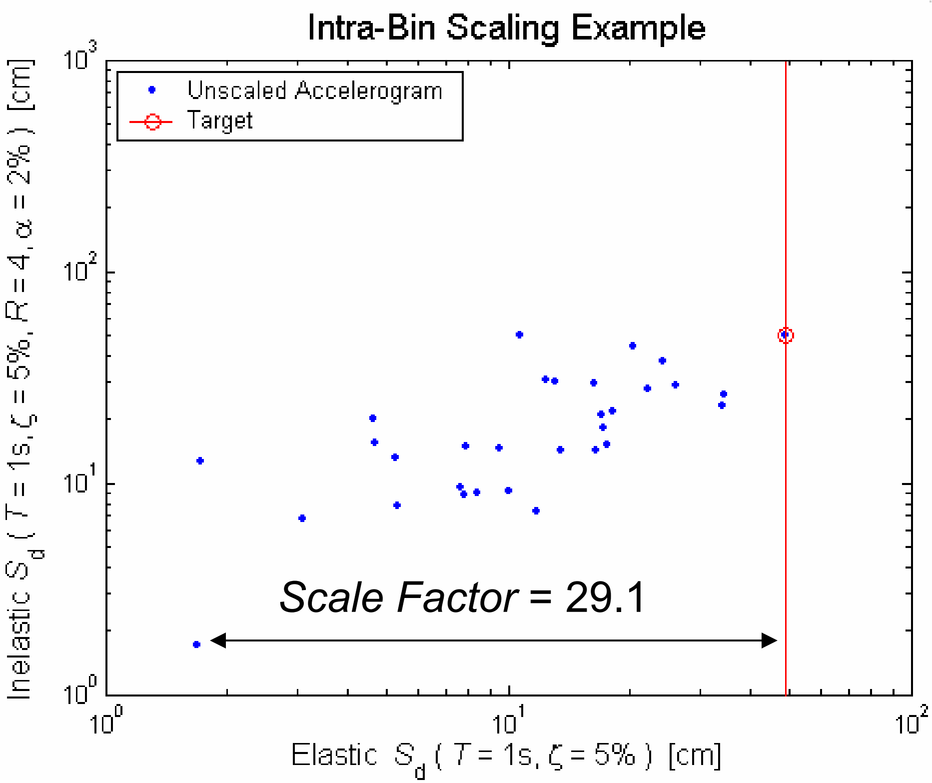
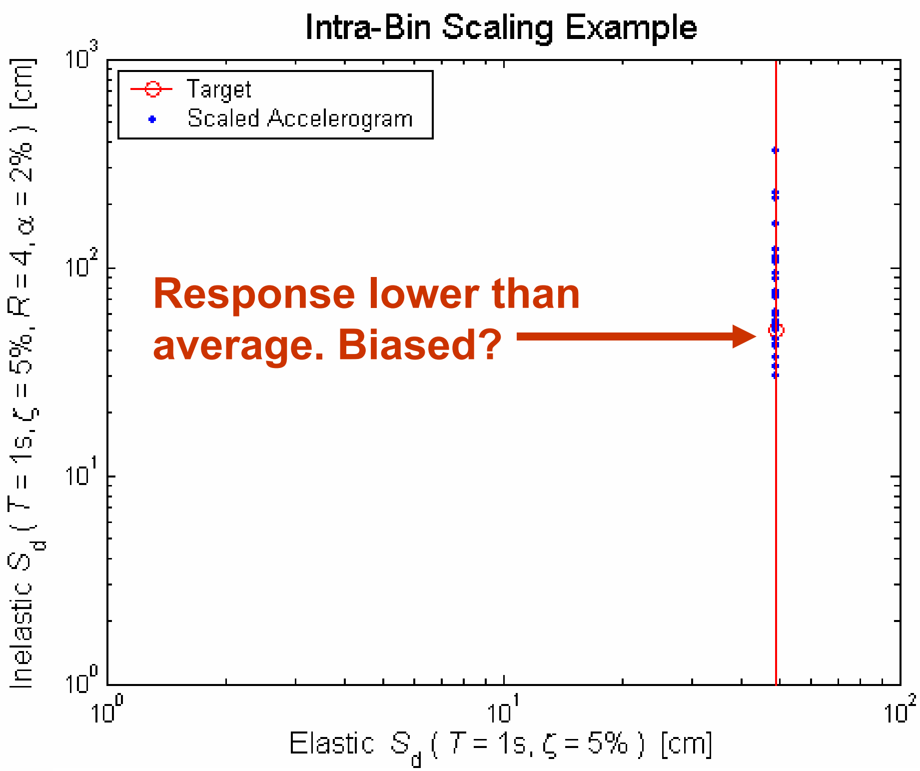
Response Plotted vs. Elastic S_d

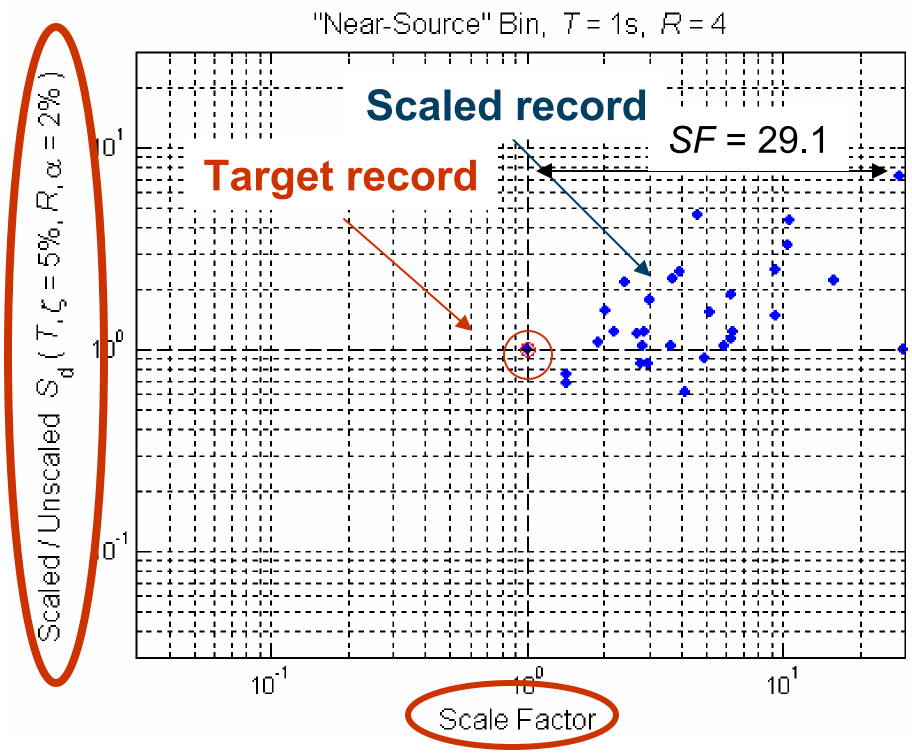




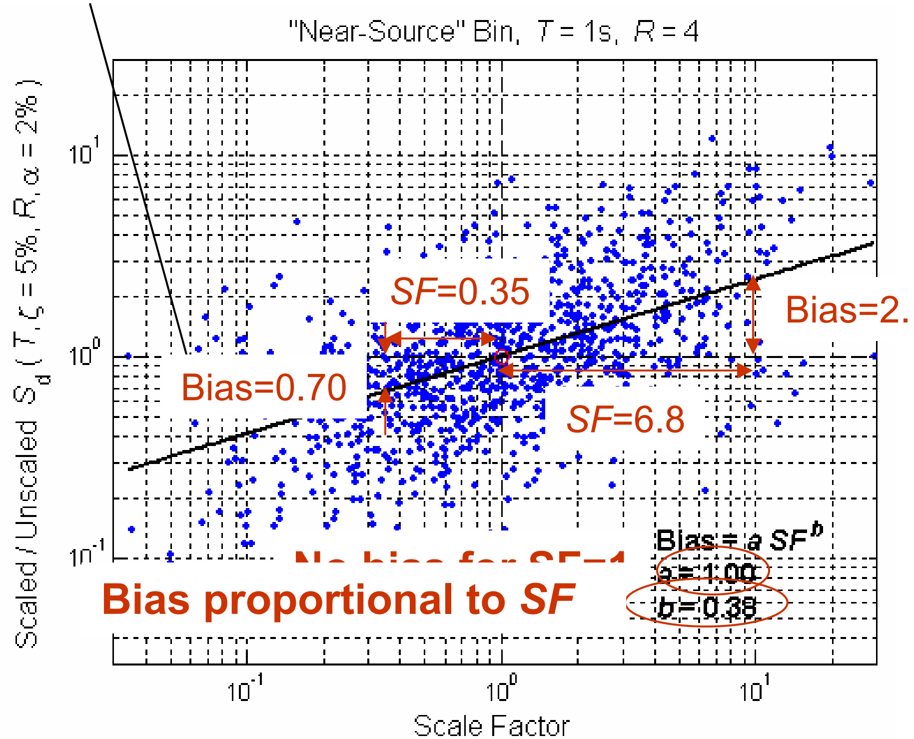
Ratio of Responses Plotted vs. Scale Factor

BIAS=*a SF* ^{b}

Bias if different than 1

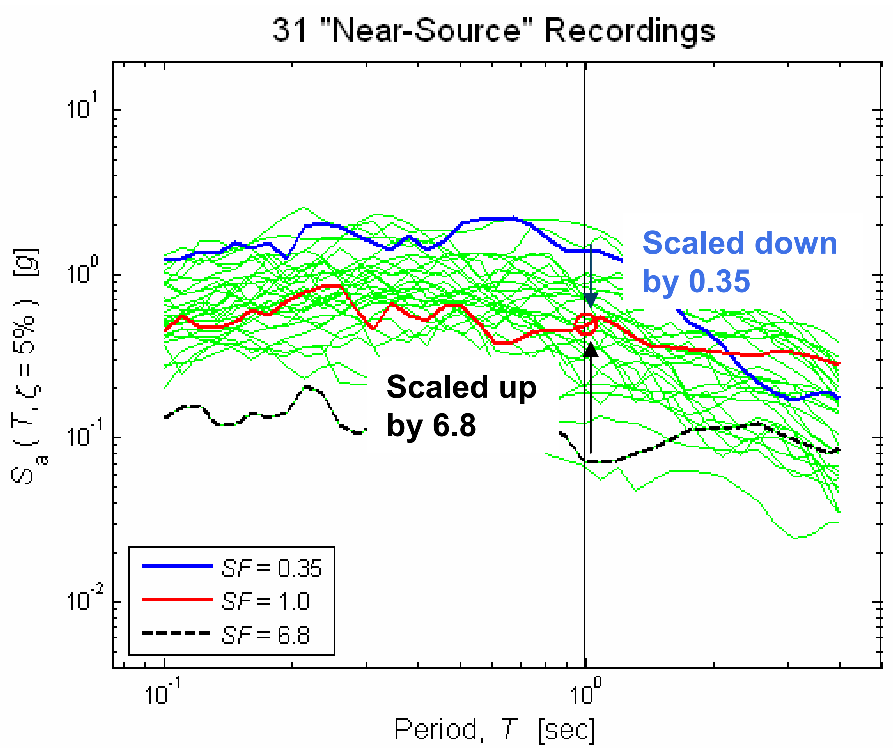


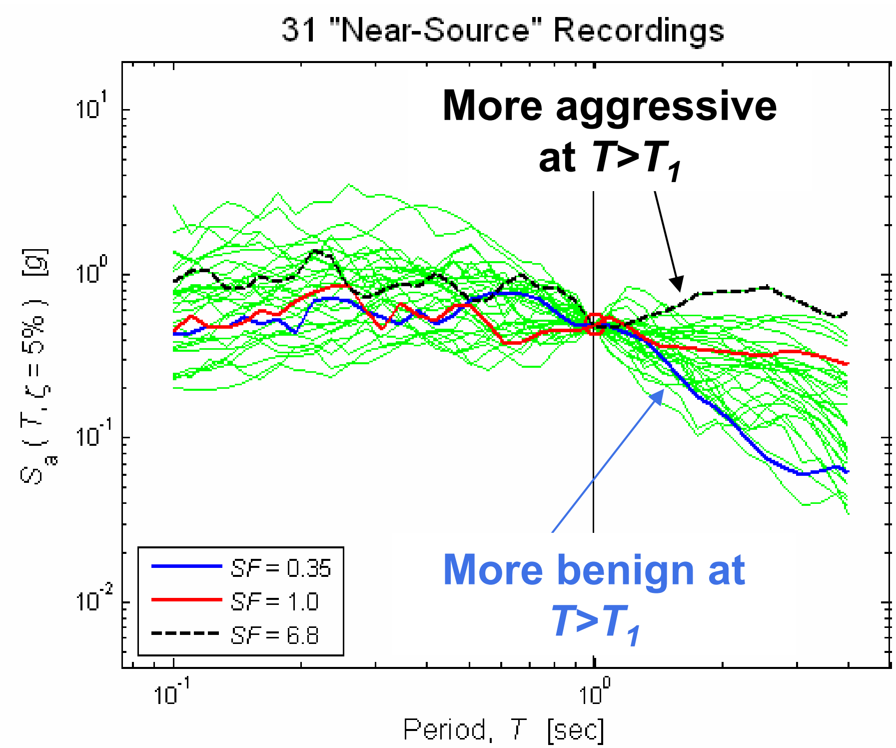
fitted line that gives the bias in median S_d^i for a given scale factor



Yes, There Is Bias? Why?

- Difference in spectral shape. On average
  - "valley" records are scaled up
  - "peak" records are scaled down

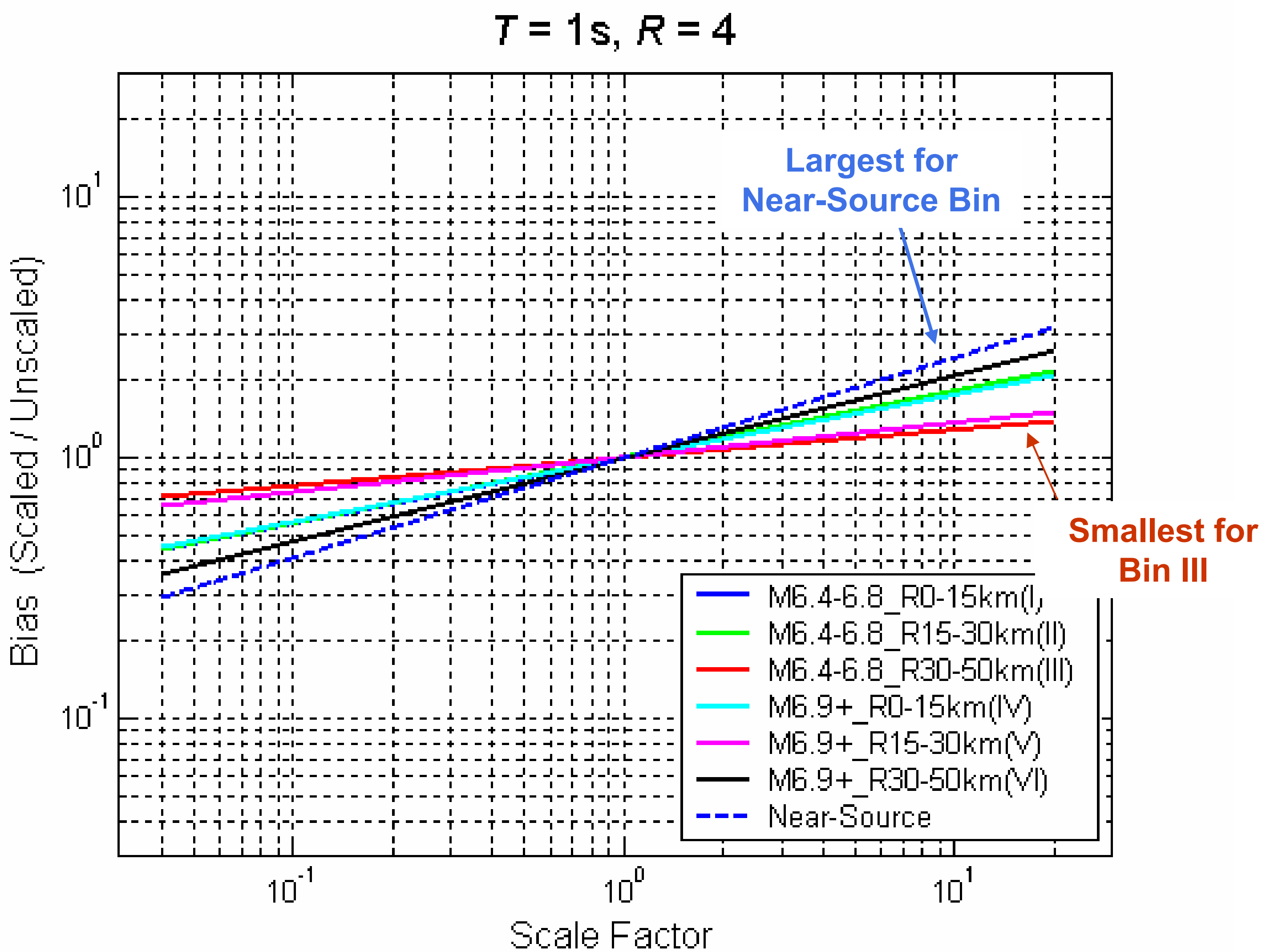




Three Meanings for This Response Bias

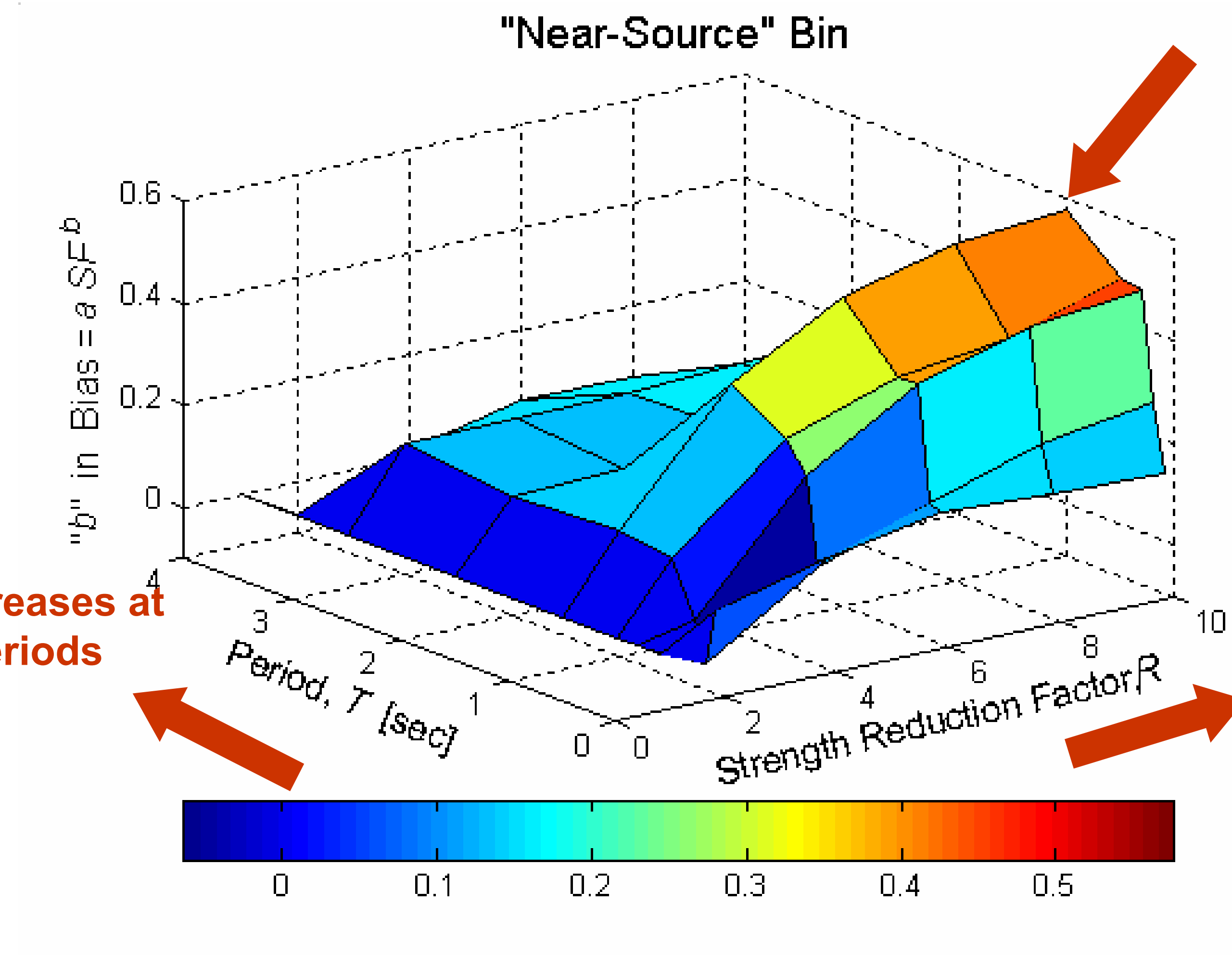
- This response bias applies to the median response of
  - Randomly selected record scaled by a *SF=x*
  - A suite of records all scaled by the same *SF=x*
  - A suite of records that, on average, are scaled by the same *SF=x* but with different scaling factors for each single record (à la Cornell)

Intra-Bin Scaling: Bias for *T*=1s, *R*=4 SDOF, All Bins



Intra-Bin Scaling: Bias for All SDOFs, Near-Source Bin

Peak due to predominant period of pulse-like records in this bin



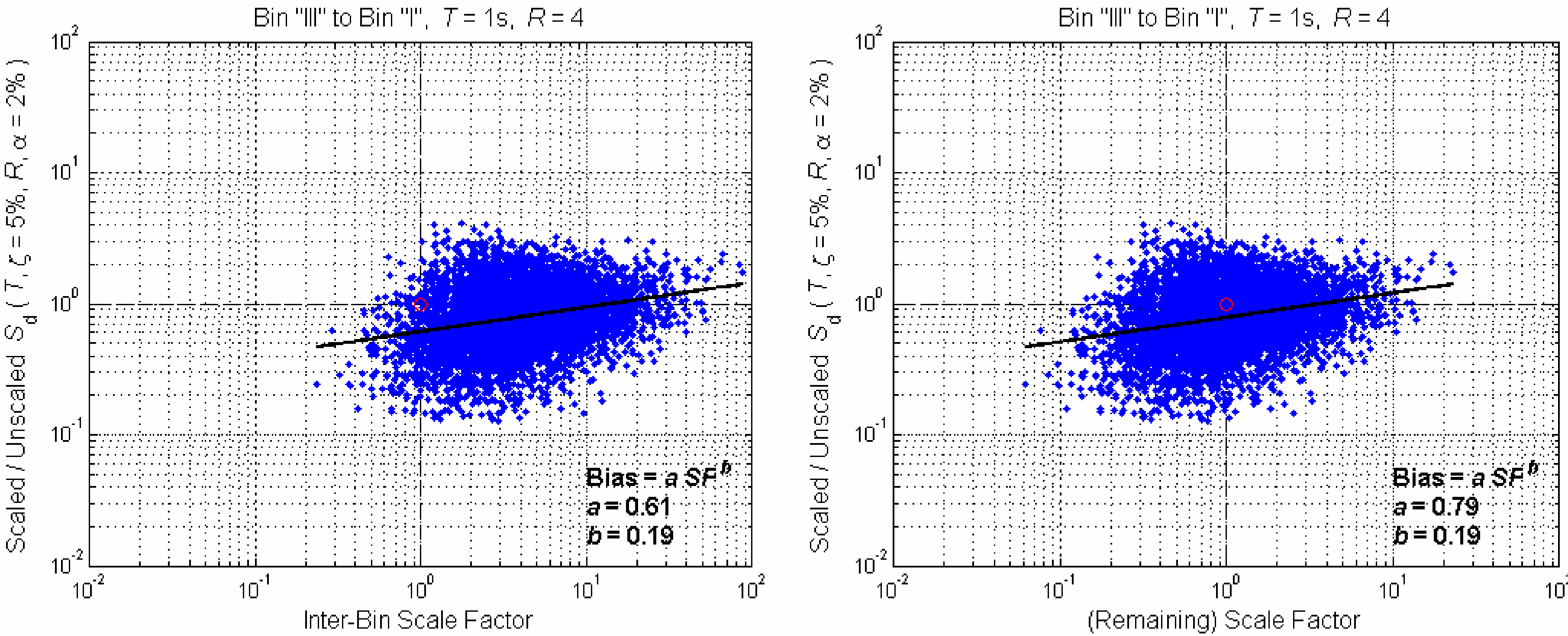
Bias decreases at longer periods

Bias increases with inelasticity

NOTE: ***a=1*** **for all SDOFs in equation BIAS=*a SF*^{b}**

Inter-Bin Scaling: *T*=1s, *R*=4 SDOF, Bin III to Bin I

- Bin III (M=6.4 to 6.8; R=30 to 50km) is weaker than Bin I (M=6.4 to 6.8; R=0 to 15km)

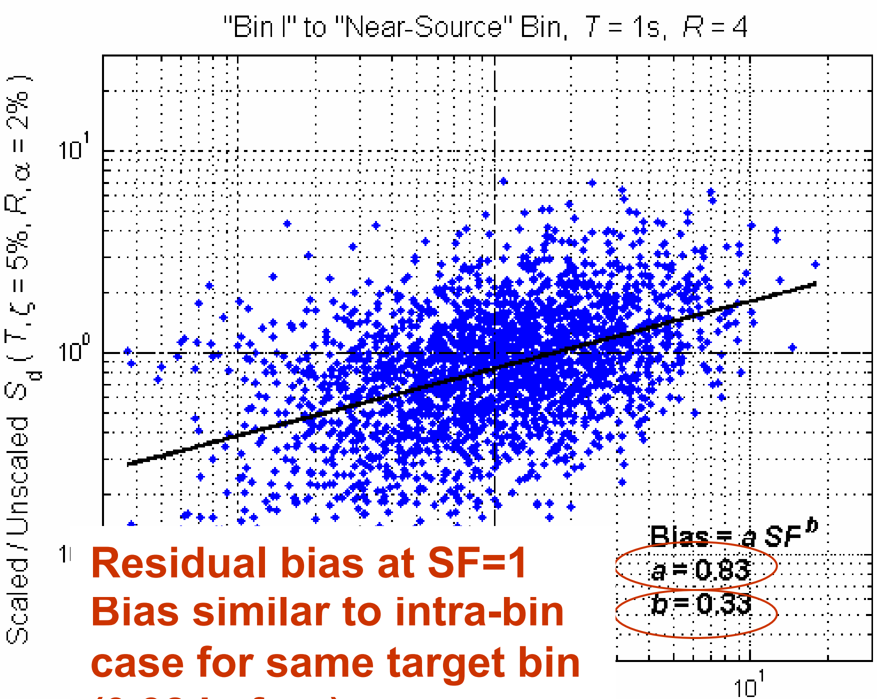


$$SF_{\text{inter-bin}} = \underbrace{r(m[S_a])}_{\text{Ratio of median Sa's target/source}} * \underbrace{SF_{(\text{remaining})}}_{\text{Remaining scaling factor (as in the intra-bin case)}}$$

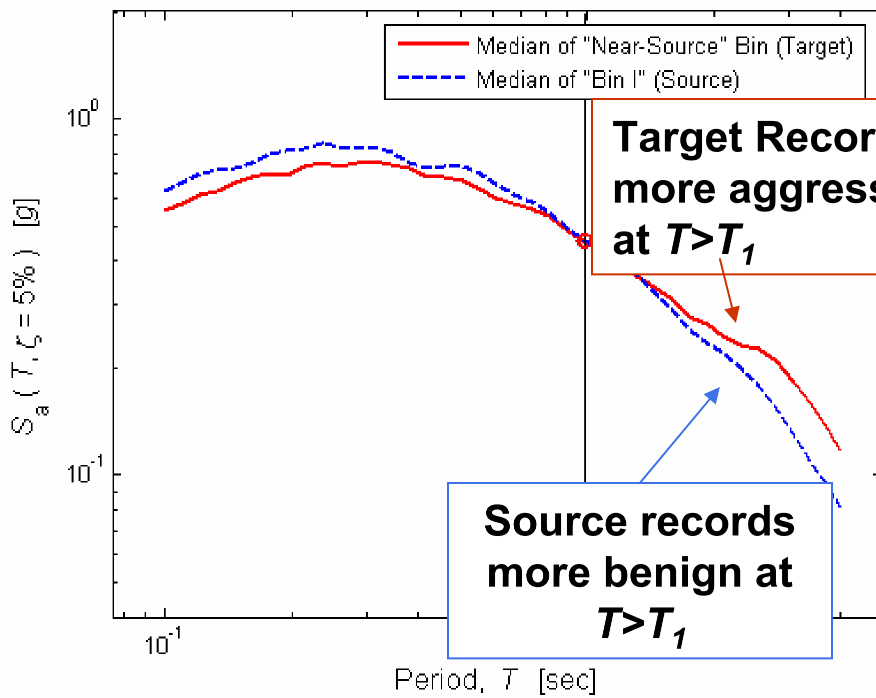
Ratio of median Sa's target/source

Remaining scaling factor (as in the intra-bin case)

Inter-Bin Scaling: *T*=1s, *R*=4 SDOF, Bin III to Bin I



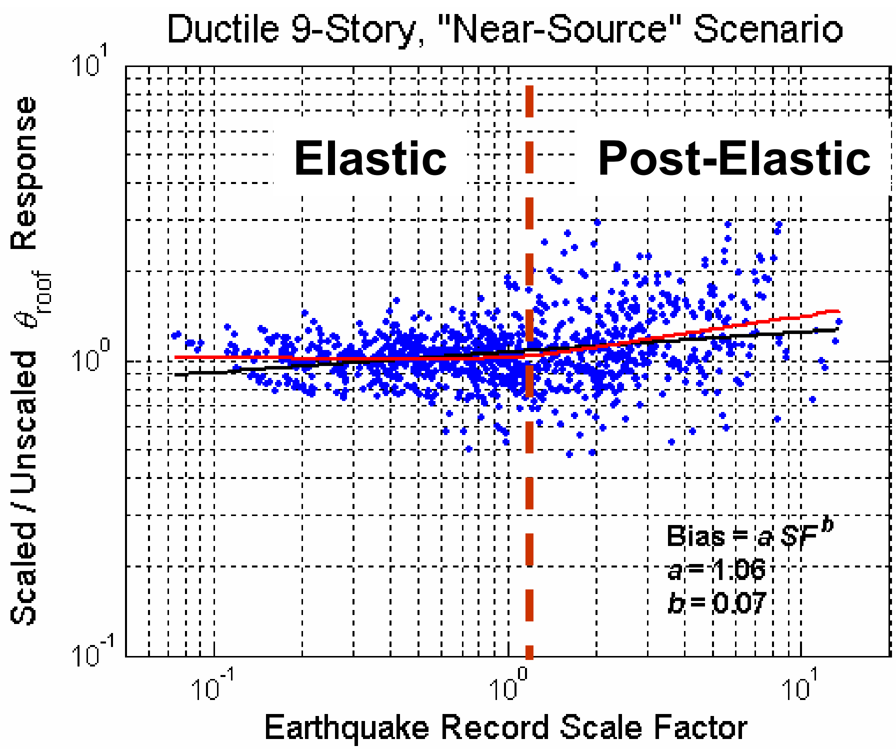
Residual bias at SF=1
Bias similar to intra-bin case for same target bin (0.38 before)

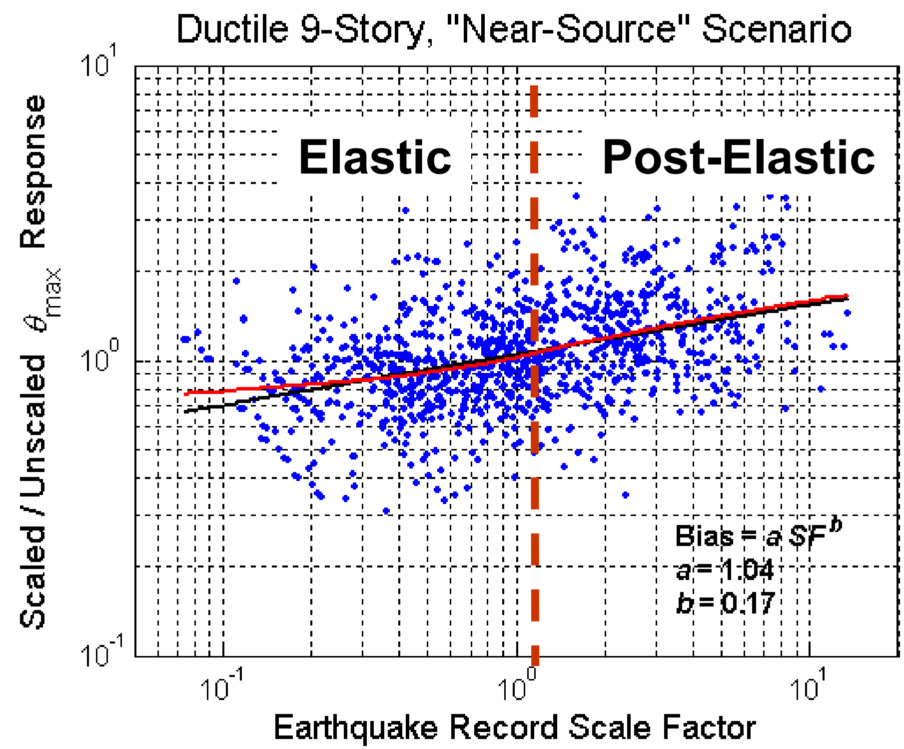


Target Records more aggressive at $T>T_1$

Source records more benign at $T>T_1$

MDOF Structure: Intra Bin Scaling, Near-Source Bin

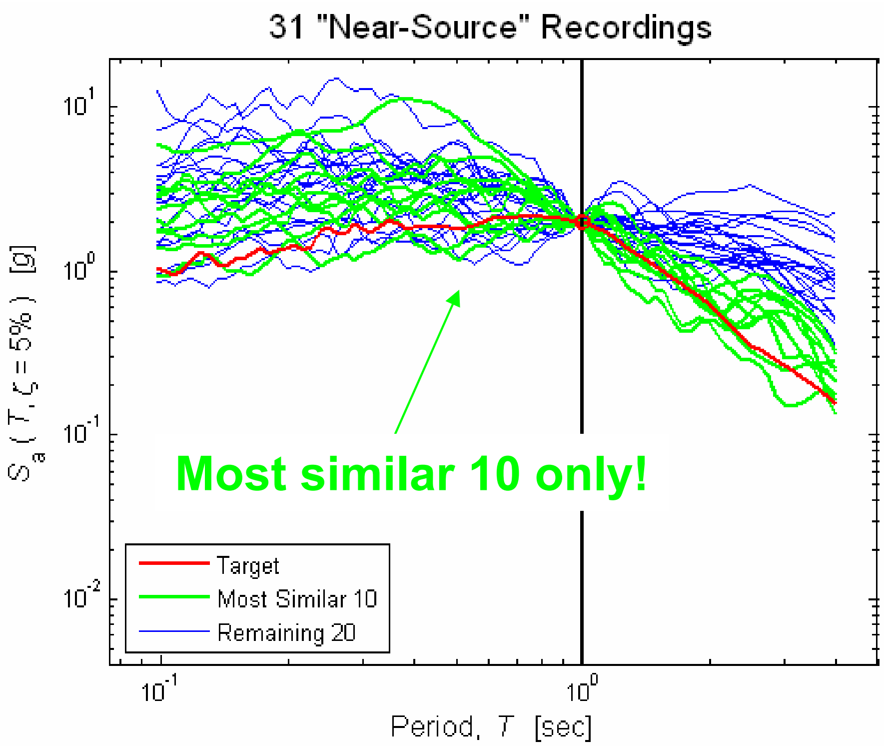


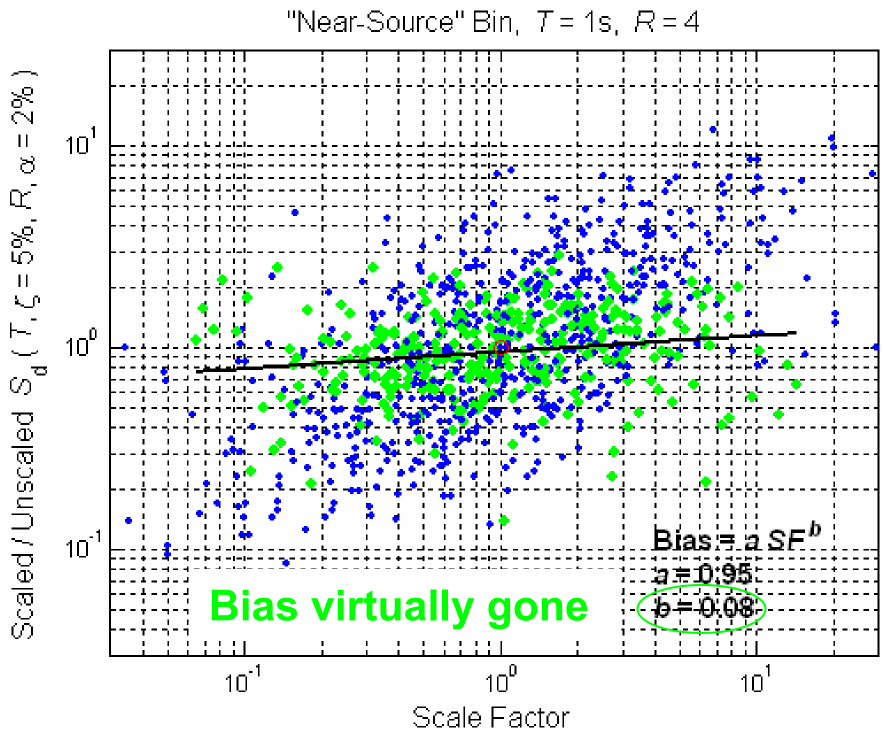


θ_{roof} is first-mode dominated
No bias in the elastic range.
Small bias in the post-elastic range

θ_{max} is sensitive to higher modes
Bias is larger and is in the elastic case too due to differences in spectral shapes (at $T<T_1$ this time!)

How Can the Bias be reduced?





Conclusions

- Scaling a randomly selected record induces bias in nonlinear response (conditional on M, R, and S_a level)
- Bias depends on
  - Scale factor
  - The fundamental period of the structure
  - The overall strength of the structure
  - The sensitivity of the response measure to higher modes
  - The ground motion scenario (e.g., *M* and *R*) of the records that are scaled
- Inter-bin scaling bias is comparable to intra-bin scaling bias for the target M and R bin case. However, there is usually an additional bias due to pre-scaling to median S_a of target bin
- Judicious selection of source records reduces considerably the response bias
- The results of this study can serve as a basis to place limits on the amount of scaling that is acceptable for a given structure (alternatively, correct response for bias)