Effect of Long Duration Ground Motions on Structural Performance

Greg Deierlein
Jack Baker
Reagan Chandramohan
Jen Foschaar
Stanford University

Background and Motivation

- Although widely believed to be important in structural performance assessment, results from prior research have been mixed and inconclusive
  - Models used did not capture cyclic deterioration of strength and stiffness
  - Effect on collapse capacity has not been studied
- Current design provisions, performance assessment studies and cyclic loading protocols do not explicitly consider ground motion duration
- Recent large magnitude events like the 2010 Chile and 2011 Tohoku earthquakes reinforce the importance of duration while providing useful new data

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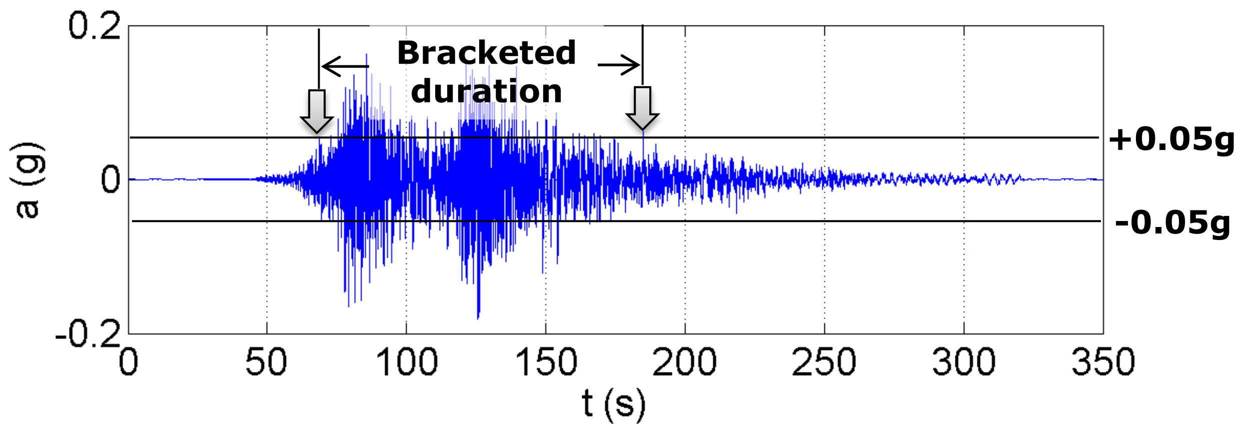
Objectives and Practical Outcomes

- Assess the effects of ground motion duration on structural performance and collapse capacity using realistic models that incorporate cyclic deterioration
  - Determine which duration metric is best suited for use in PBEE framework
  - Create a benchmark long duration ground motion set
  - Identify situations where ground motion duration is expected to be important
- Evaluate and propose how to incorporate the effects of duration into
  - The PBEE framework, in hazard characterization and ground motion selection
  - Building codes and design criteria
  - Cyclic loading protocols

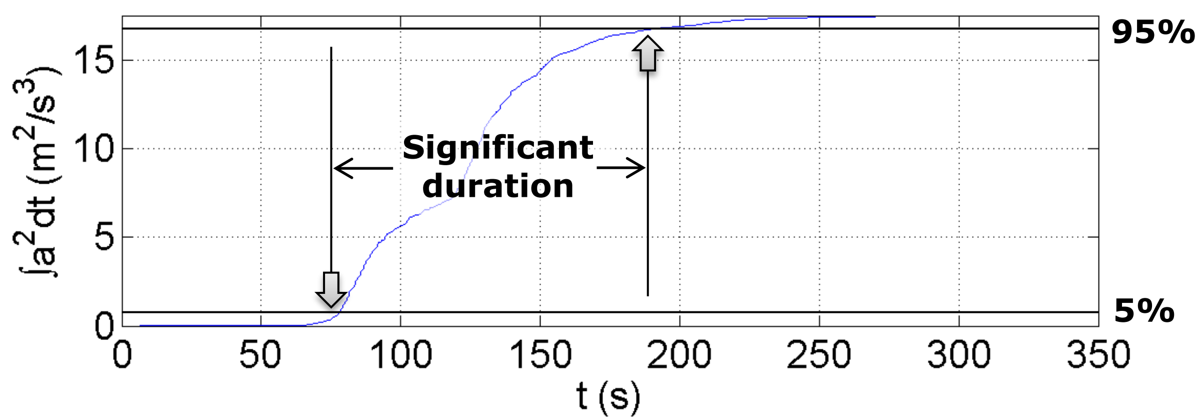
Ground motion duration metrics

- Bracketed duration



Thresholds
- 0.05g
- 0.1g
- 0.2g

- Significant duration



Ranges
- 5-95%
- 5-75%
- 2.5-97.5%

Ground motion duration metrics

- Arias Intensity
  - $Arias\ Intensity = \frac{\pi}{2g}\int_0^{t_{max}} a(t)^2 dt$
- Cumulative Absolute Velocity
  - $CAV = \int_0^{t_{max}} |a(t)|\, dt$
- I_D (Cosenza and Manfredi, 1997)
  - $I_D = \frac{\int_0^{t_{max}} a(t)^2 dt}{PGA \times PGV}$

Comparison of duration metrics

- Tested each duration metric by selecting long duration ground motion sets (based on each metric's definition of duration) from a pool of ground motions

Desired properties	Bracketed duration	Significant duration	Arias Intensity	CAV	I_D
Uncorrelated to common IMs like PGA and Sa(1s)	✓	✓	✗	✗	✓
Unaffected by scaling	✗	✓	✗	✗	✓
Does not bias spectral shape	✓	✓	✓	✓	✗

5-95% Significant duration (t_{5-95}) identified as most suitable duration metric

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Pilot study on Steel Braced Frame

- Rapidly deteriorating structural system
- Modeled in OpenSees

Rotational Spring

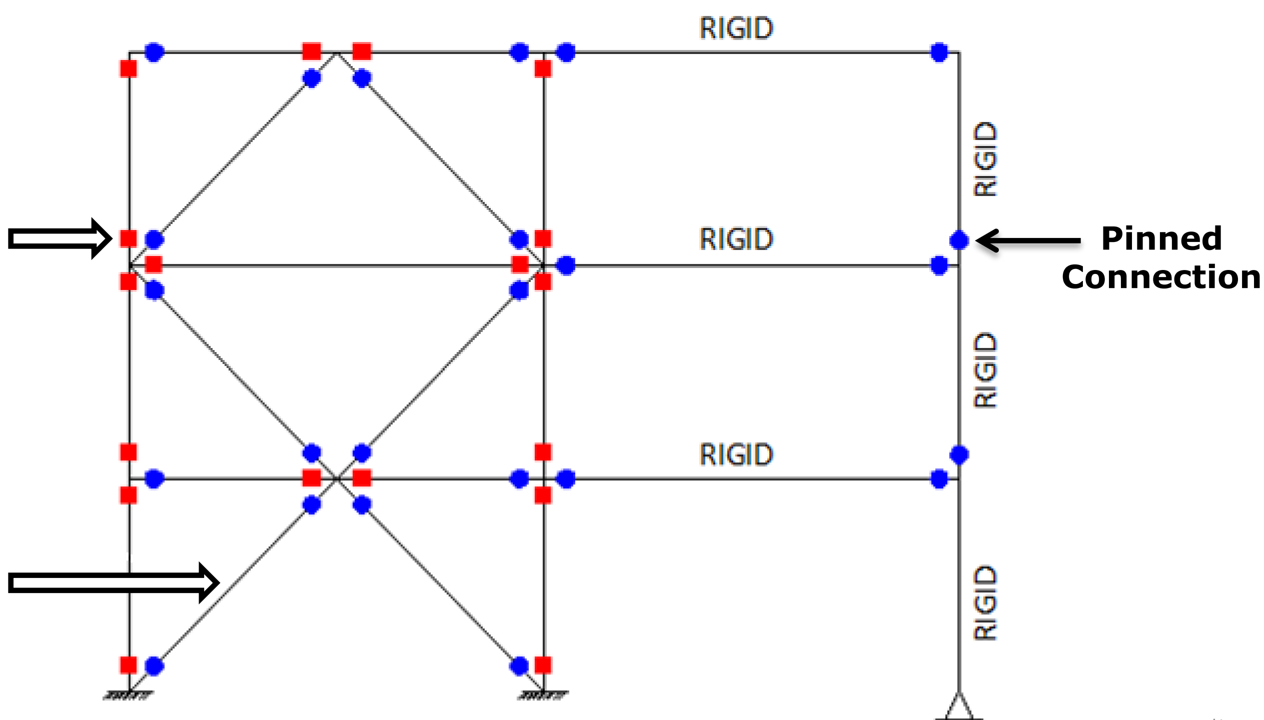
Zero-length hinge

Modified Ibarra-Medina-Krawinkler bilinear model with in-cycle and cyclic degradation

Brace

Force-based fiber element

Giuffre-Menegotto-Pinto steel model with isotropic strain hardening and low-cycle fatigue effects (*Uriz and Mahin, 2004*)



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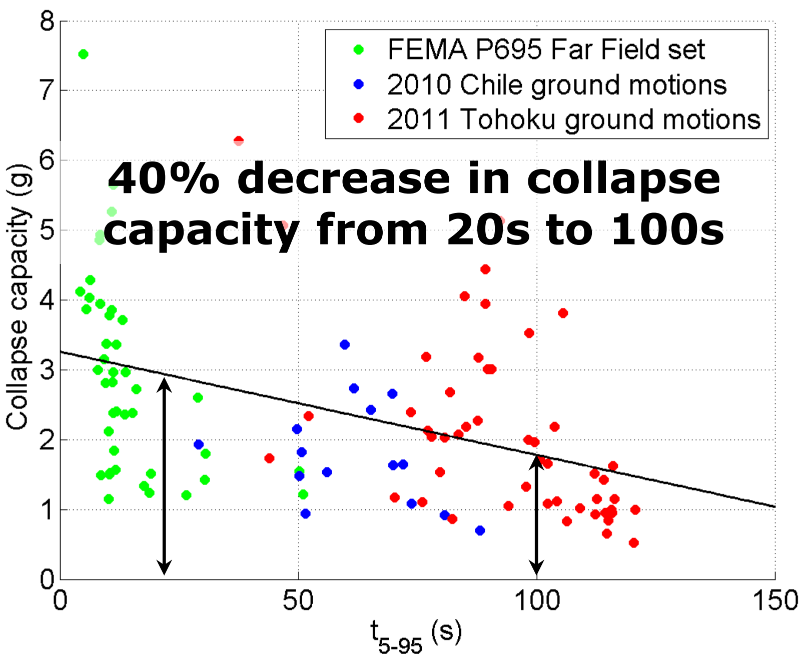
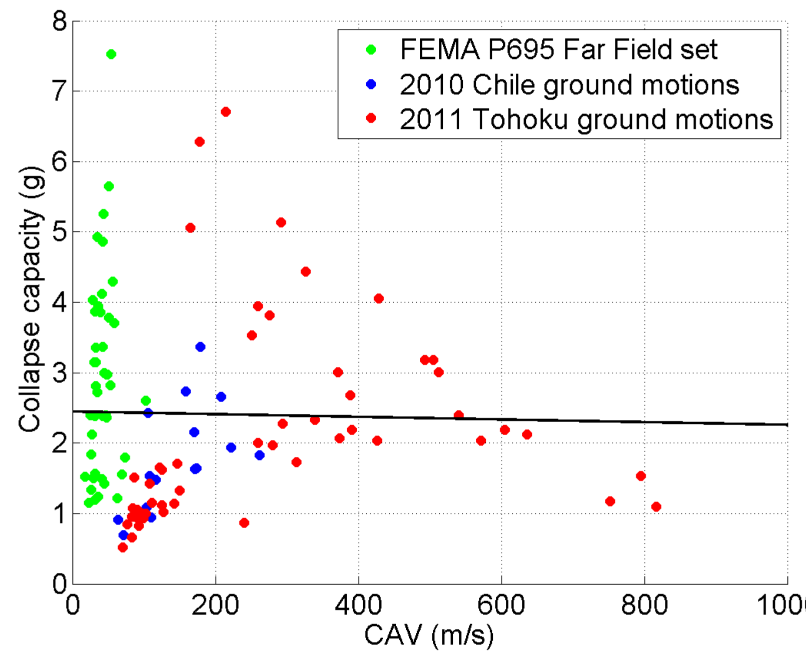
Incremental Dynamic Analysis Results





- Observed significant decrease in collapse capacity with duration
- 5-95% Significant duration (t_{5-95}) best captured this effect

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Extended long duration record set

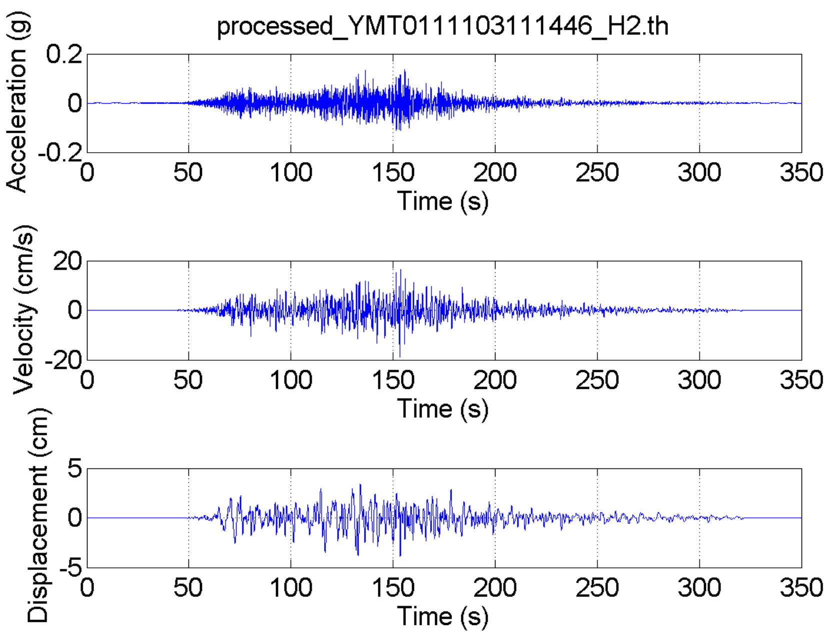
- Earthquakes considered
  - 1974 Peru
  - 1979 Imperial Valley, USA
  - 1985 Chile
  - 1985 Michoacan, Mexico
  - 1995 Kobe, Japan
  - 1999 Chi-Chi, Taiwan
  - 2003 Hokkaido, Japan
  - 2004 Niigata, Japan
  - 2007 Chuetsu, Japan
  - 2008 Iwate, Japan
  - 2008 Wenchuan, China
  - 2010 Chile
  - 2010 El Mayor Cucapah, USA
  - 2011 Tohoku, Japan

- ~2000 horizontal record pairs acquired in total
- Ground motions filtered and baseline corrected (*Boore and Bommer, 2005)*
- Ground motions screened out
  - Mean PGA < 0.1g
  - Mean PGV < 10cm/s
  - t_{5-95} < 45s
  - Maximum of 25 record pairs retained from each event
- 106 record pairs remained

Two sources of long duration ground motions

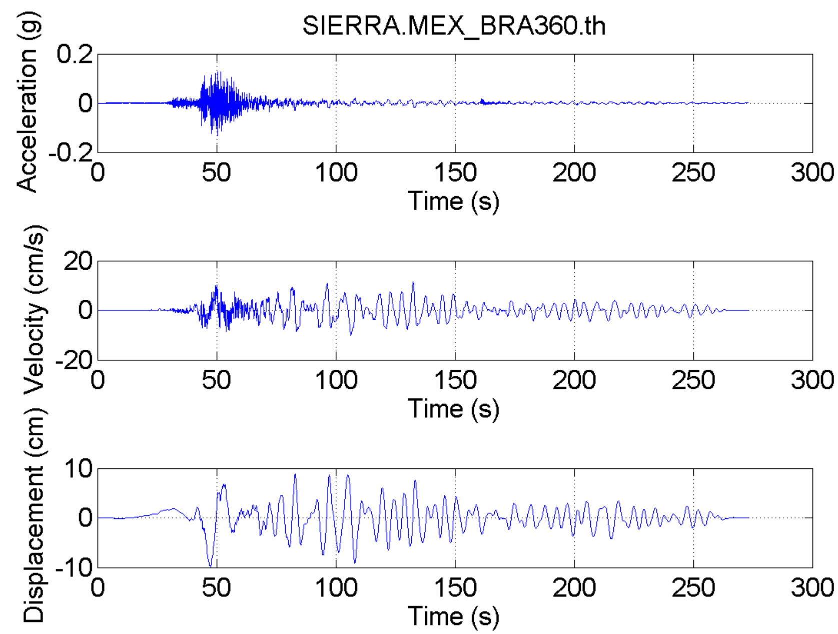
Long Rupture

2011 Tohoku Earthquake, (M_w 9.0)



Site Effects

2010 El Mayor Cucapah Earthquake, (M_w 7.2)



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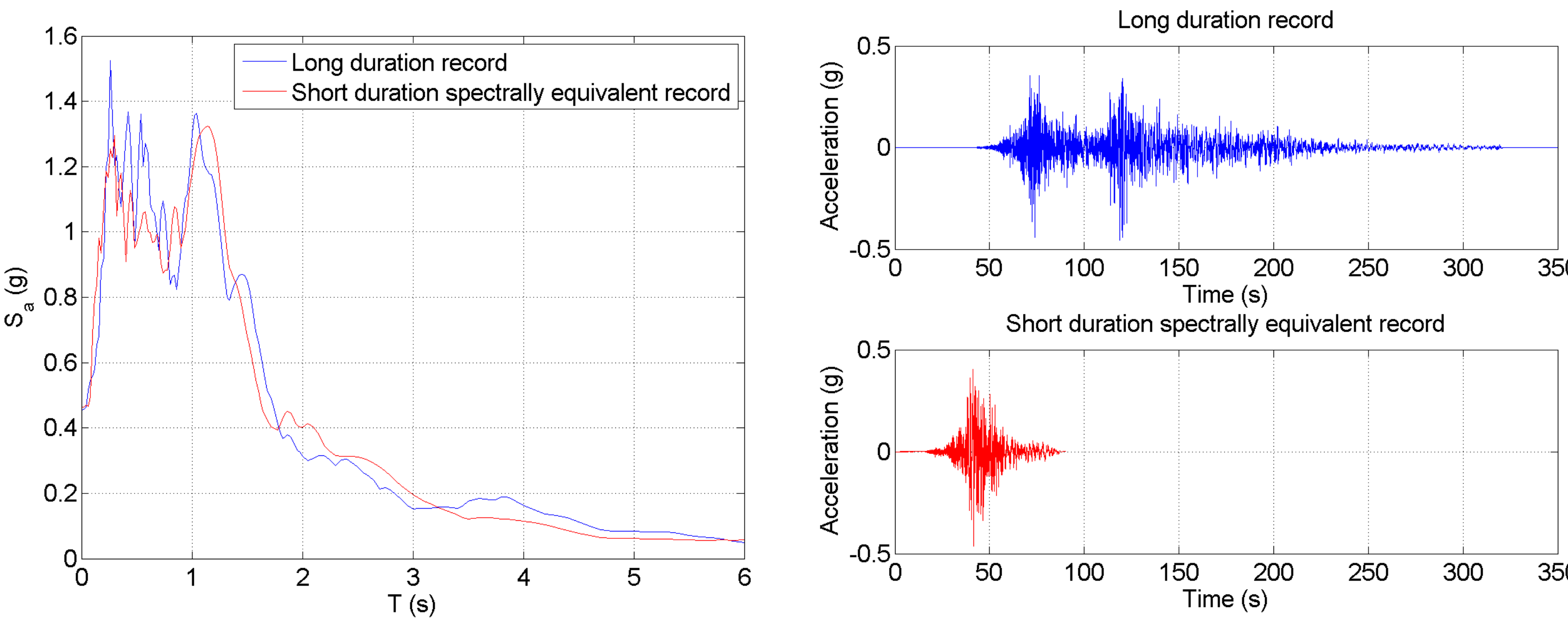
Spectrally Equivalent Short Duration Set

- For every long duration ground motion, a corresponding short duration ground motion was chosen from the PEER NGA West 2 database with a similar spectral shape
- Created as a control for the effect of spectral shape



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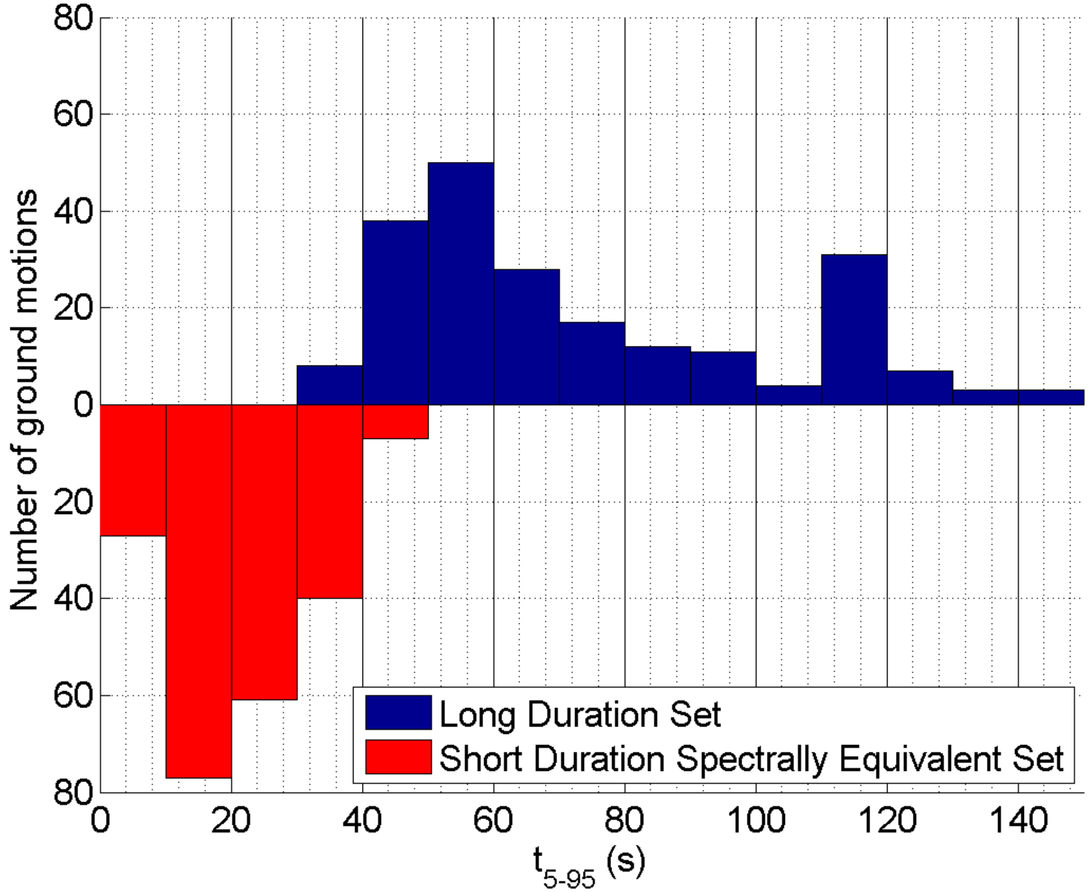
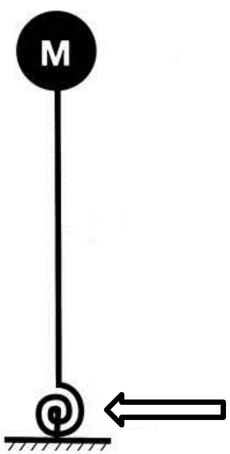
Comparison of ground motion durations



Concrete Bridge Pier Model

- Concrete column tested by PEER and NEES at UC San Diego was modeled in OpenSees as an SDOF system
- Reasons for choice of structure
  - Study effect of duration on representative bridge column
  - SDOF systems facilitate parametric studies without higher mode effects



Rotational Spring

Zero-length hinge

Modified Ibarra-Medina-Krawinkler peak-oriented model with in-cycle and cyclic deterioration

Initial hysteretic energy dissipation capacity $E_t = \gamma M_y \theta_y$

Deterioration governed by dissipated hysteretic energy as

$$\beta_i = \left(\frac{E_i}{E_t - \sum_{j=1}^{i} E_j}\right)^c$$

$$F_i = (1 - \beta_i) F_{i-1}$$

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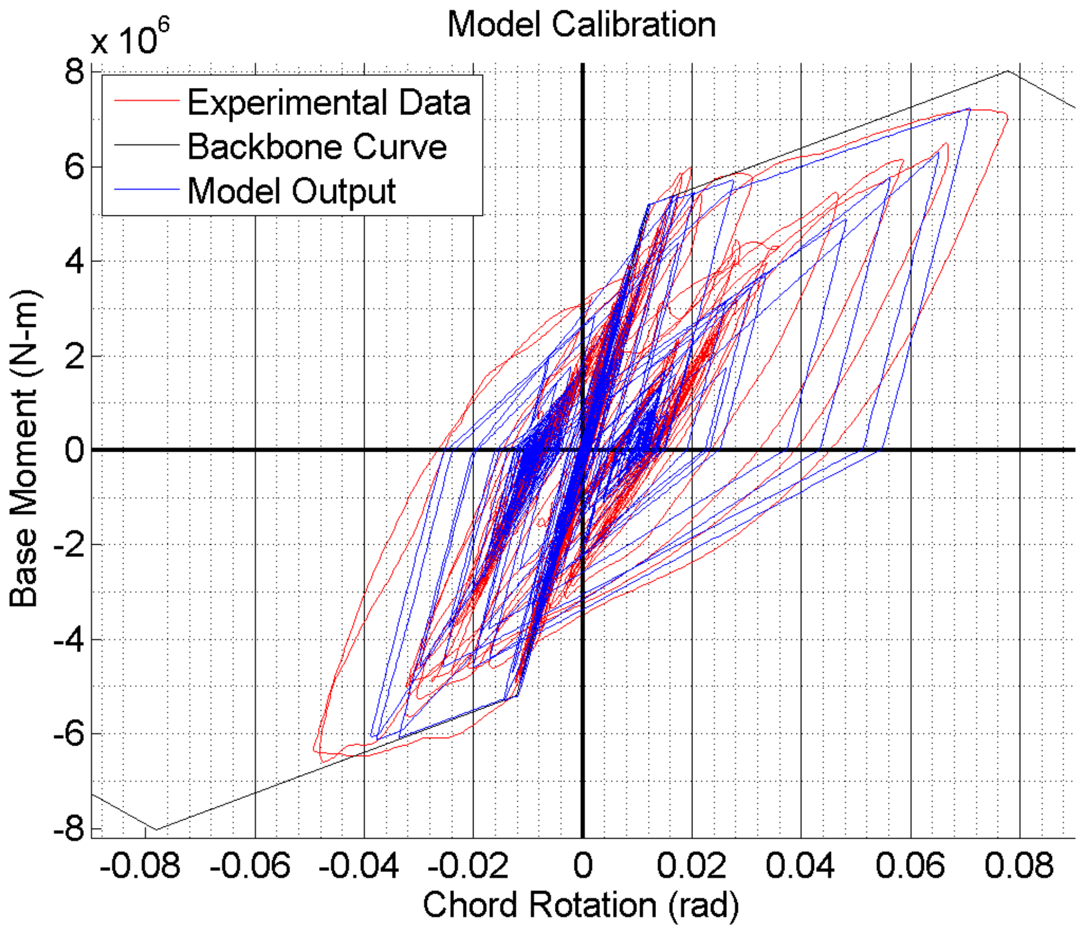
Calibration to test data



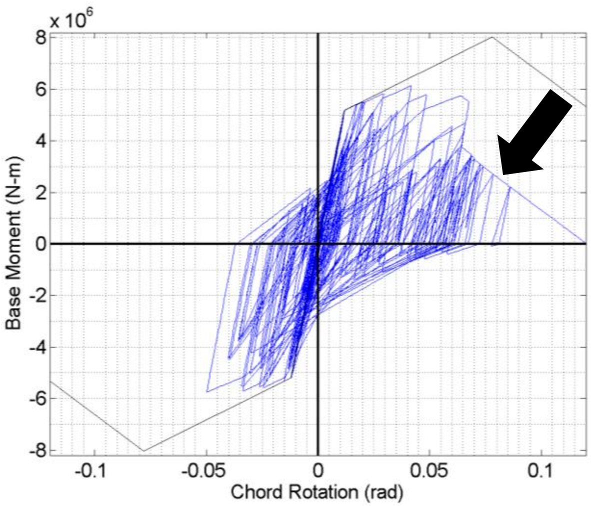
Period = 1.1s

$\gamma = 120$

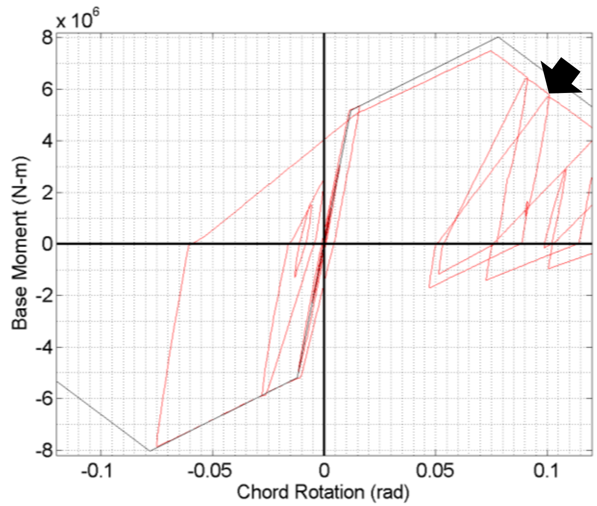
Effect of duration and γ on hysteresis plots

- Entire long duration set, spectrally equivalent short duration set and FEMA P695 Far Field sets used in analysis

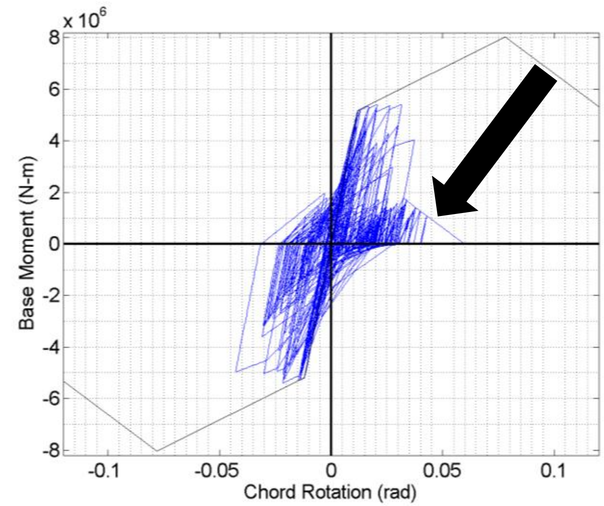
Typical long duration ground motion at collapse



Typical short duration ground motion at collapse



Same long duration ground motion at collapse with low γ



- Value of γ expected to control effect of duration on collapse capacity
- Analysis repeated for different periods and different values of γ

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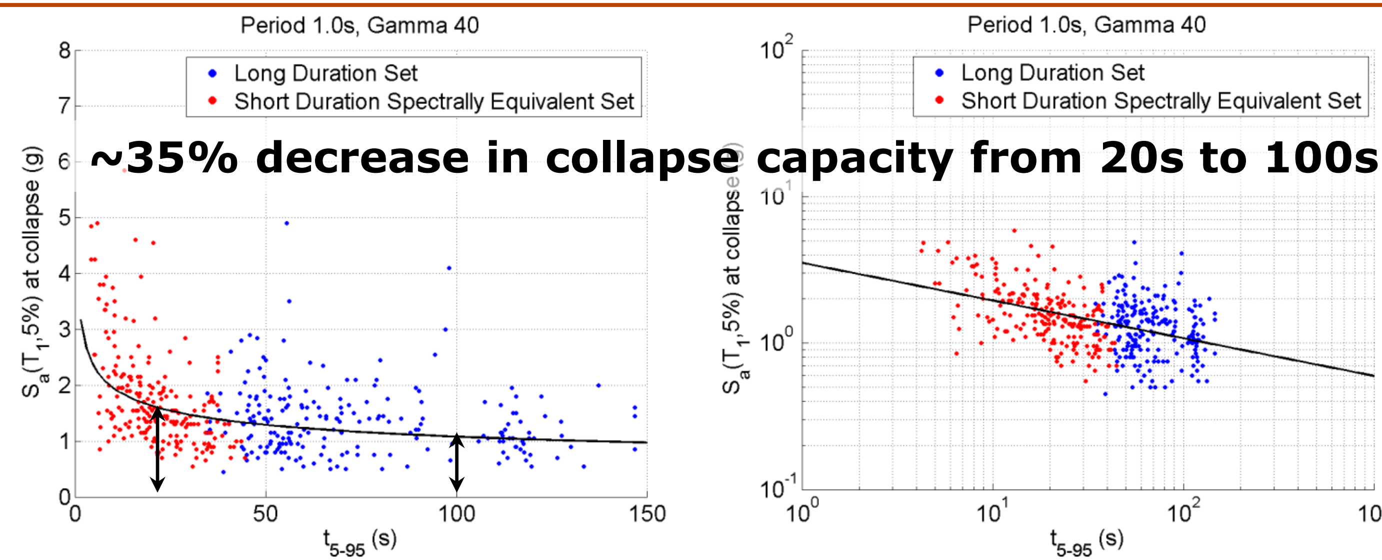
Collapse capacity vs. t_{5-95}

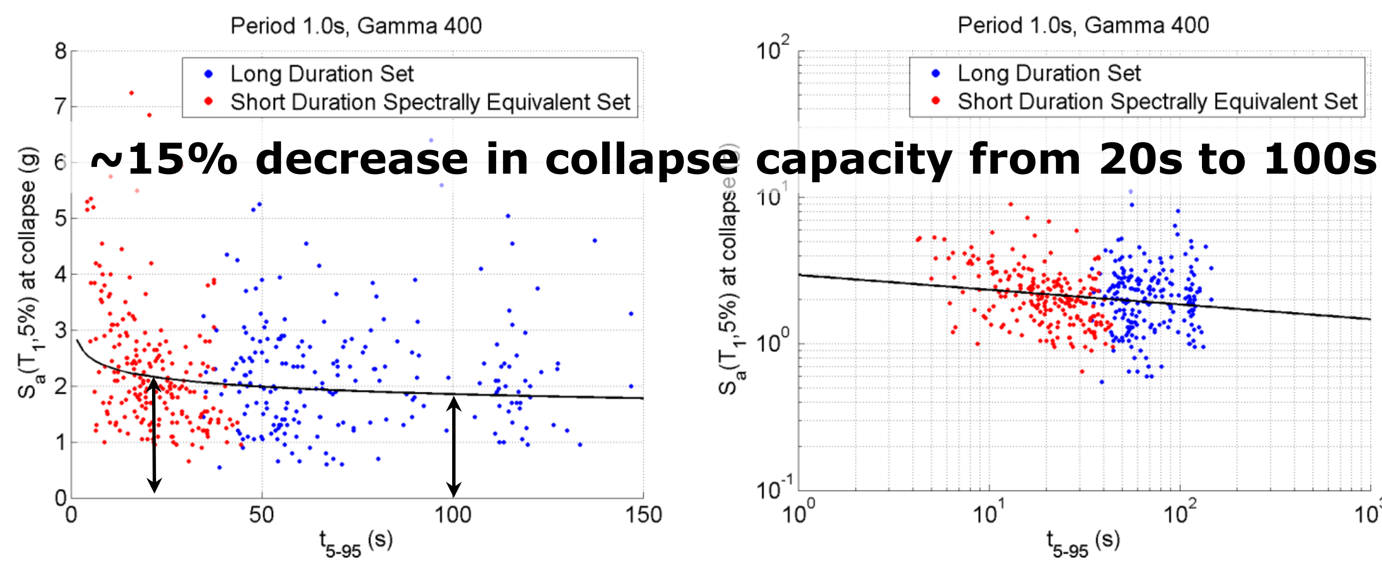
$\gamma = 40$

~35% decrease in collapse capacity from 20s to 100s



$\gamma = 400$

~15% decrease in collapse capacity from 20s to 100s



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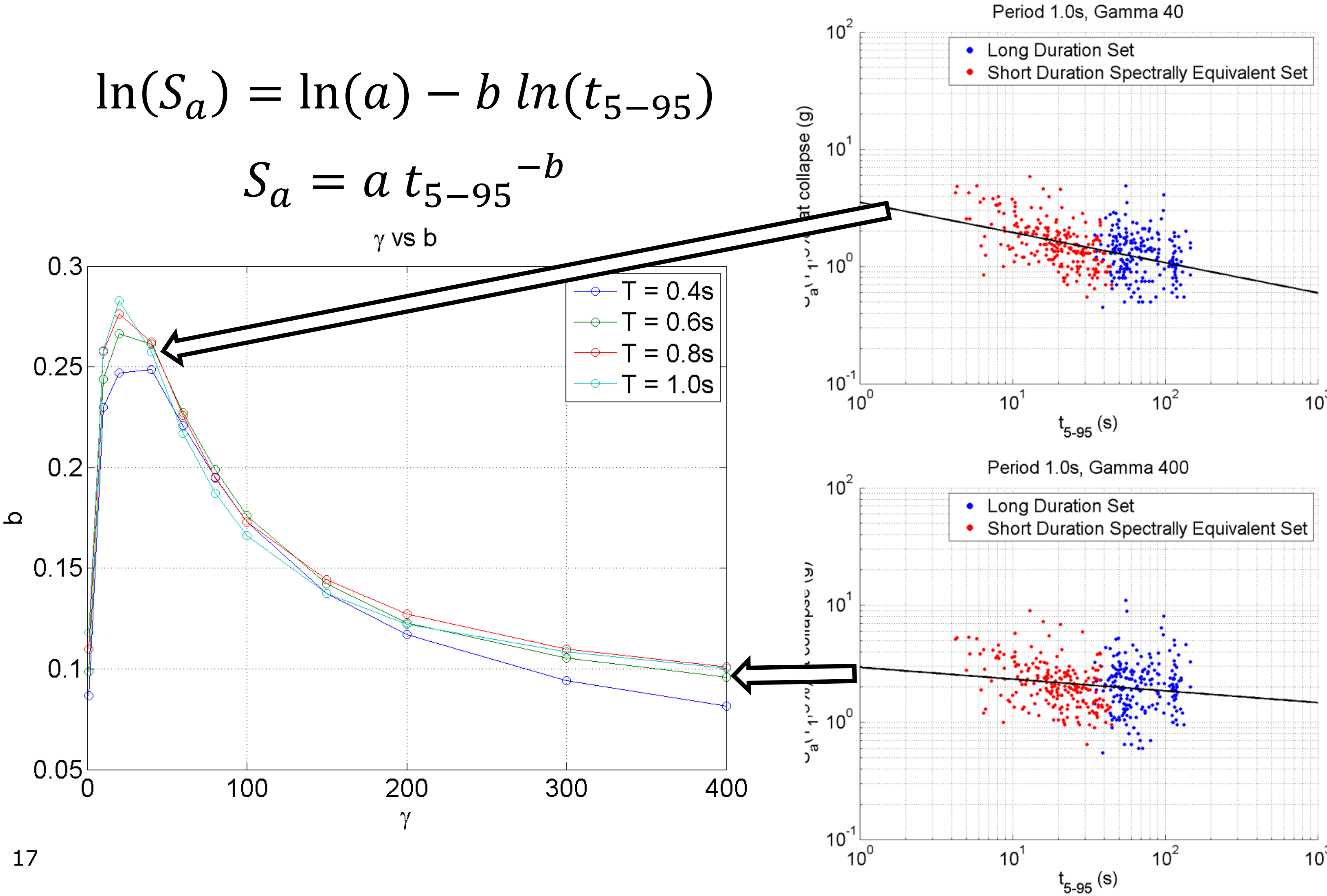
γ vs. b

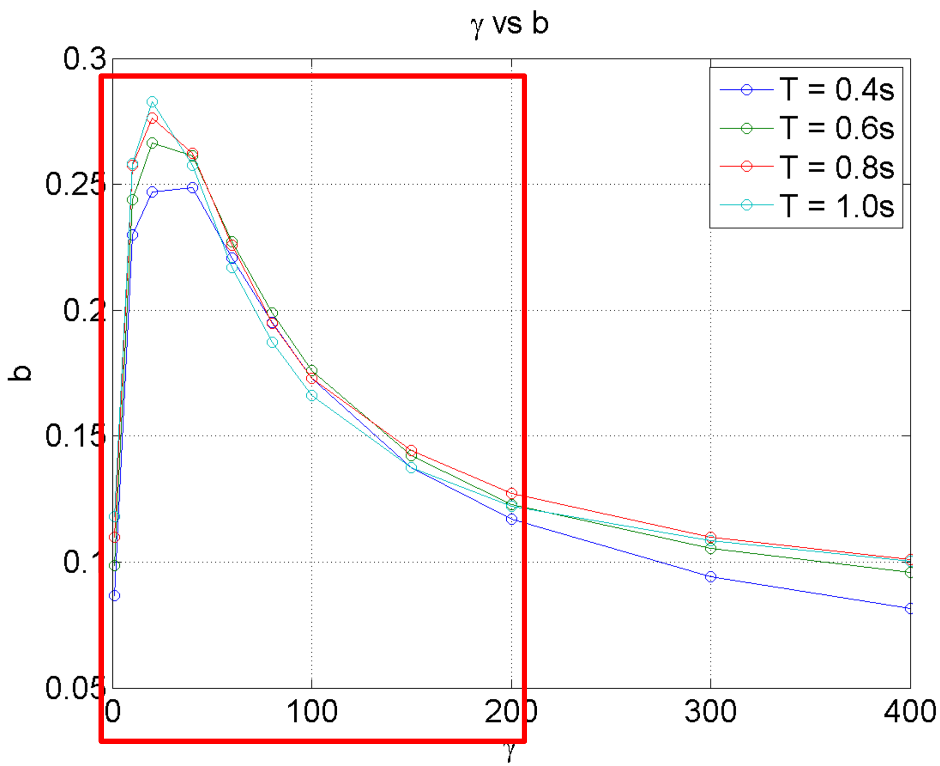
$$\ln(S_a) = \ln(a) - b\ ln(t_{5-95})$$

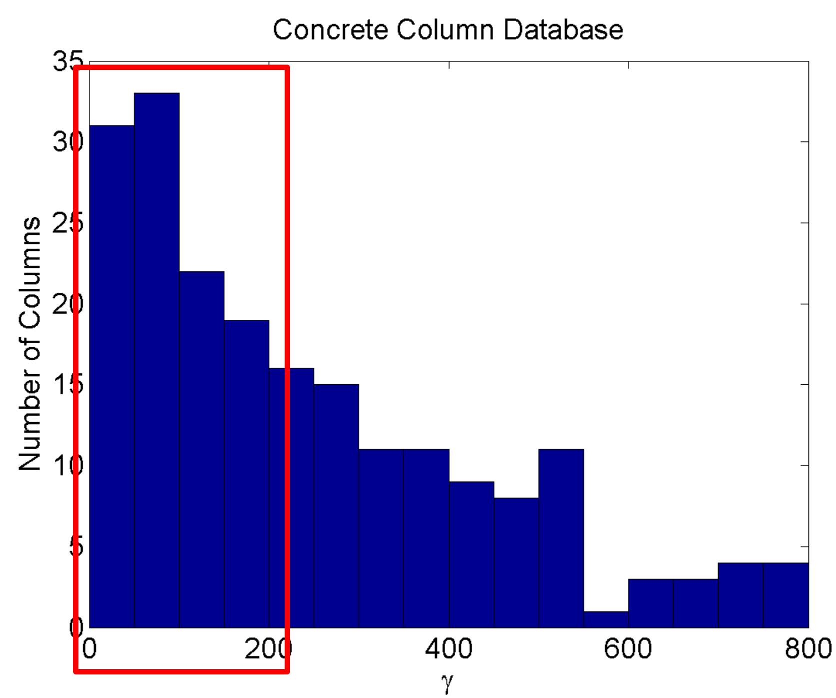
$$S_a = a\ t_{5-95}{}^{-b}$$



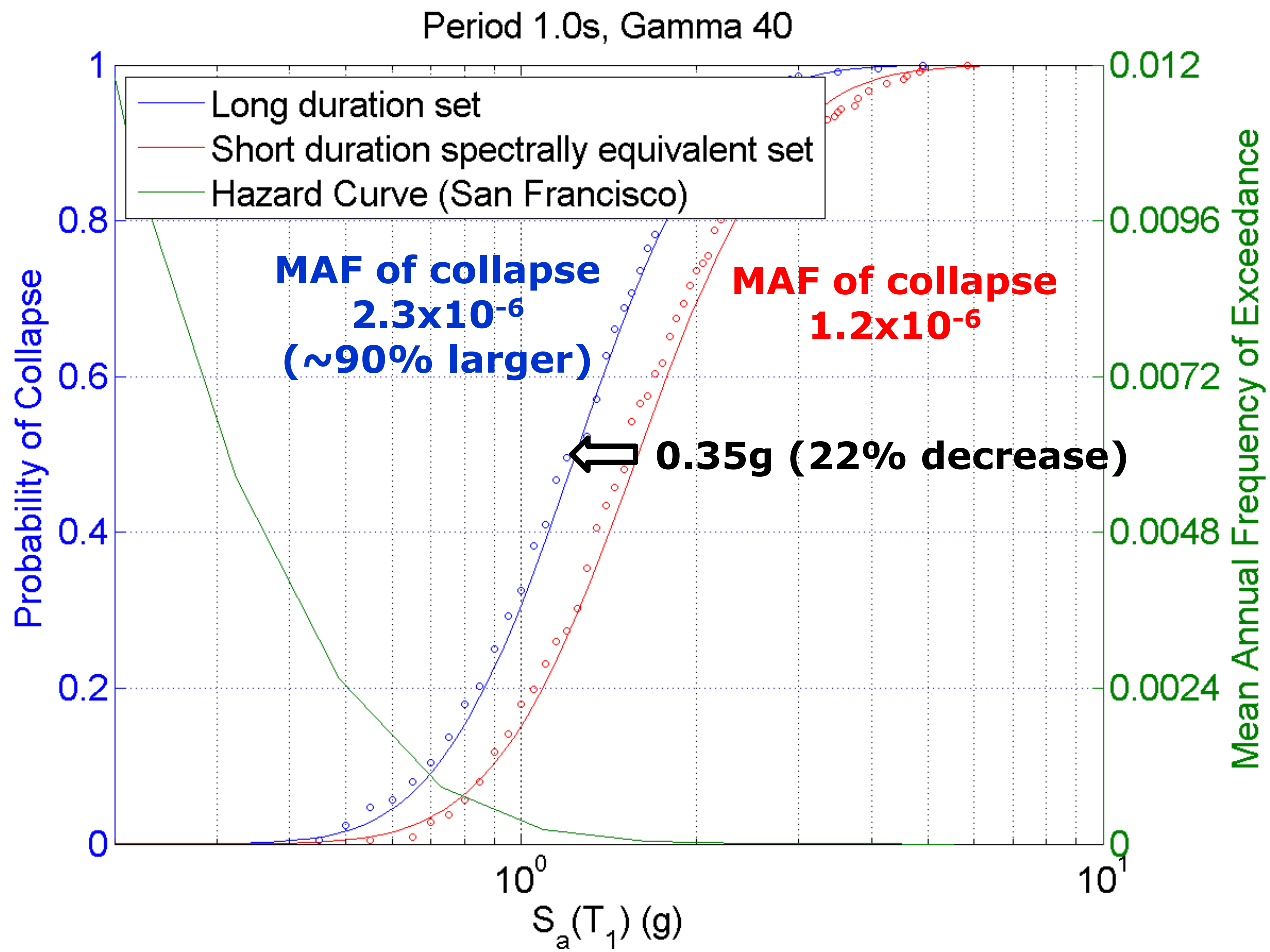
Observed values of γ

Concrete column calibrations from Haselton et al., 2008
Based on PEER Structural Performance Database





Effect on Mean Annual Frequency of Collapse



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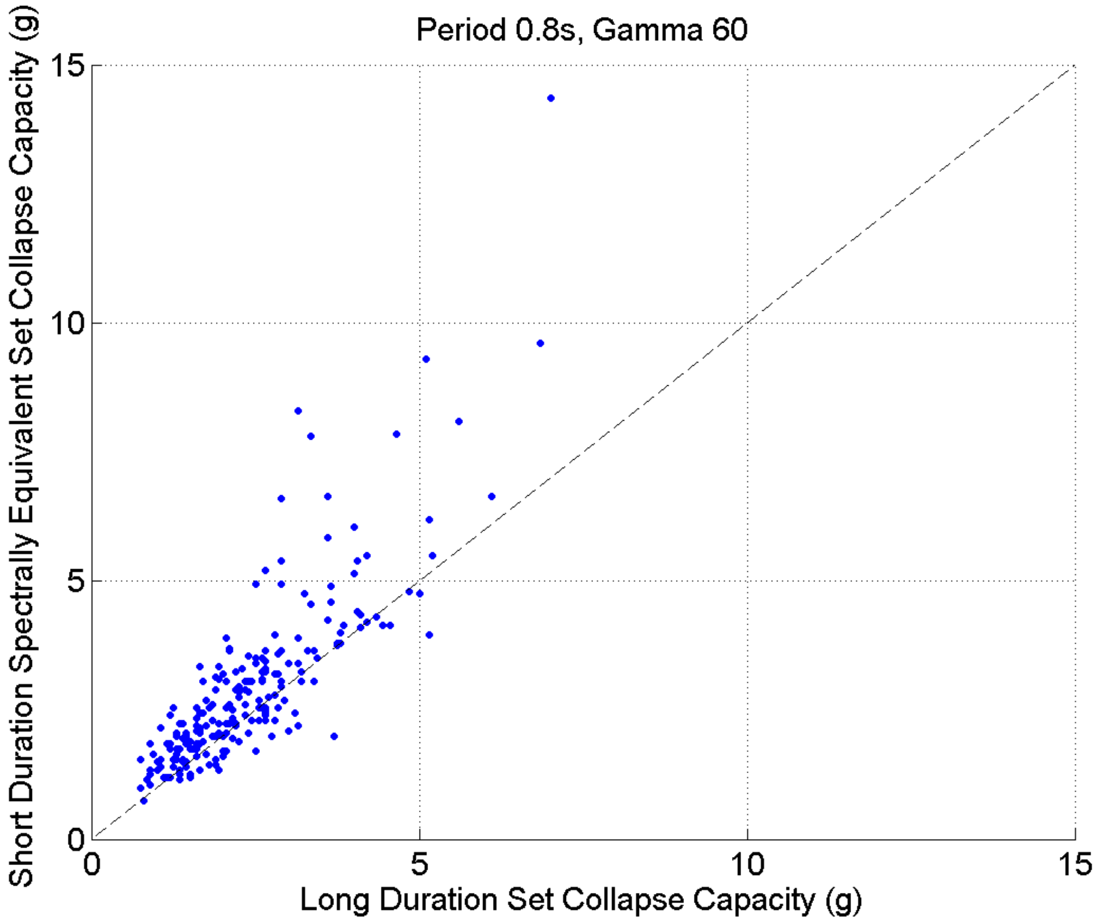
Effect of spectrally matching ground motions on collapse capacity



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Summary of findings

- Duration can have a significant impact on the collapse capacity of structures
  - Depends on hysteretic energy dissipation capacity
  - Reduction in collapse capacity from 20s to 100s
    - Braced frame example: ~40%
    - Concrete column example: ~35% (~90% increase in MAF of collapse)
- Use of realistic (deteriorating) structural models and careful ground motion selection allowed for rigorous assessment of duration effects
- 5-95% significant duration is most effective among common metrics used to quantify ground motion duration

Future work

- Study the sensitivity of duration effects on other parameters used to characterize SDOF systems
- Extend the study of SDOF systems to MDOF bridge archetype models
- Evaluate methods of incorporating effects of duration into:
  - The PBEE framework
  - Building codes and design criteria
  - Cyclic loading protocols

Thank you!

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