QuakeCoRE Flagship 4:
Seismic Performnce of Non-structural Elements
University of Canterbury
July 31st, 2018

UME understanding and managing extremes

IUSS Scuola Universitaria Superiore Pavia

Estimation of Floor Spectra in Nonlinear Multi-Degree of Freedom Systems

David P. Welch

IUSS Pavia, Italy; Stanford University

Timothy J. Sullivan

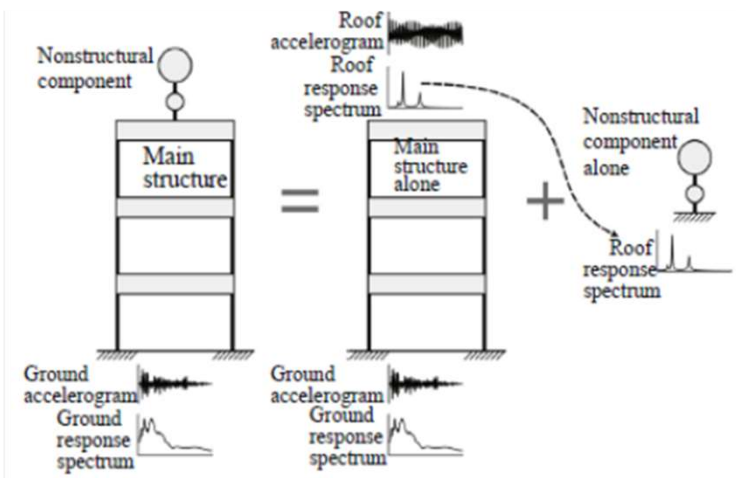
University of Canterbury, New Zealand

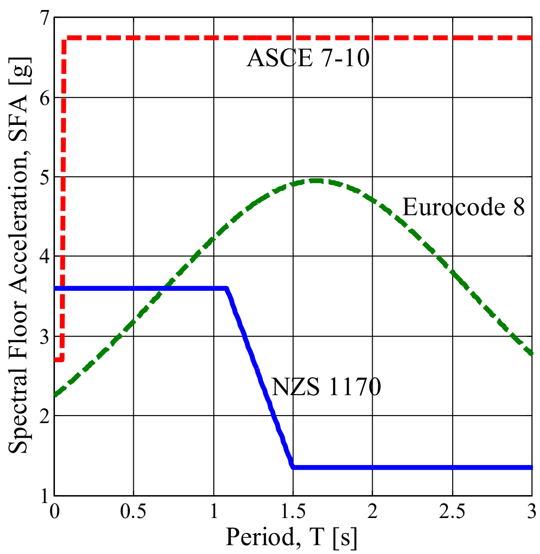
Motivation and Overview

- Increased attention has been given to the seismic design of nonstructural components (NSCs) due to their large role in seismic risk of modern buildings

- Floor response spectra using time-history analysis is a principal tool in understanding the loading of NSCs, yet is both time consuming and limited in applicability

- Current code equations represent highly generalized approximations of floor response spectra out of the need for simplicity



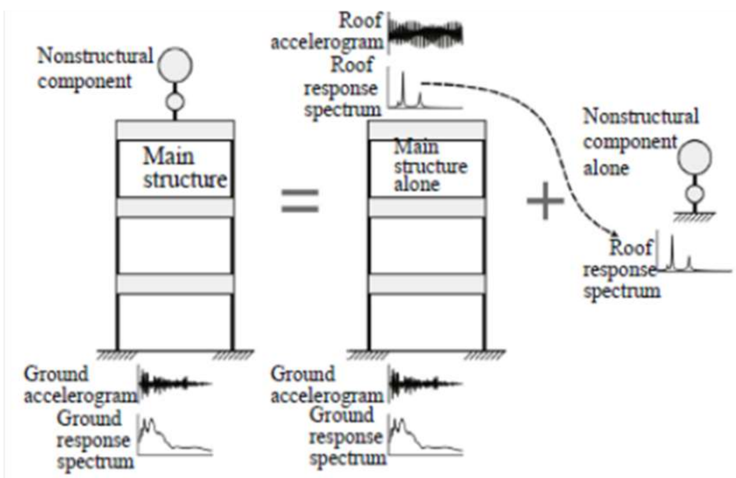


UME
understanding and managing extremes

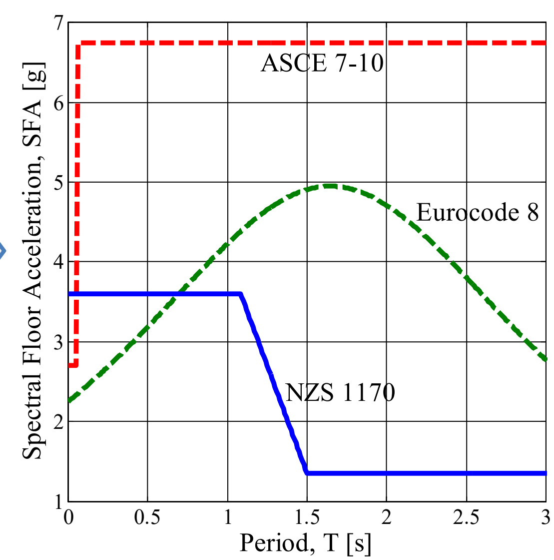
IUSS
Scuola Universitaria Superiore Pavia

Motivation and Overview

- Increased attention has been given to the seismic design of nonstructural components (NSCs) due to their large role in seismic risk of modern buildings
- Floor response spectra using time-history analysis is a principal tool in understanding the loading of NSCs, yet is both time consuming and limited in applicability
- Current code equations represent highly generalized approximations of floor response spectra out of the need for simplicity

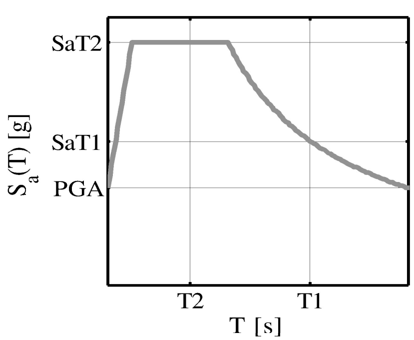


Provide improved feedback while maintaining simplicity

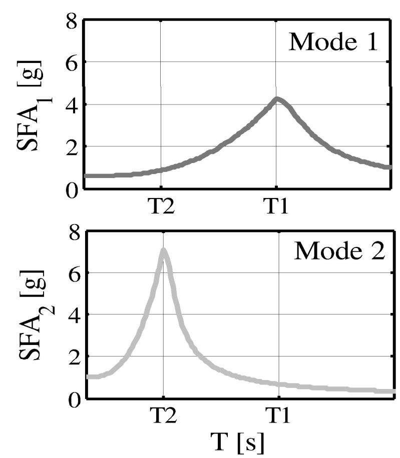


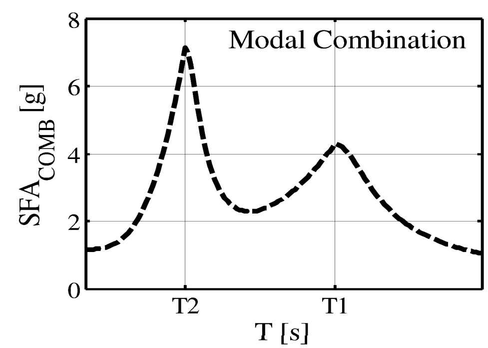
Motivation and Overview

- A **modal superposition approach** is used to approximate the spectral floor acceleration (SFA) demands



$$a_{\max,j,i} = \frac{\phi_{j,i}}{\sum \phi_{j,i} m_j} m_{e,i} S_{a,i}$$





Modal analysis and spectral demands → Modal peak floor acceleration demands → Modal floor spectra contributions → Combine modal responses

UME
understanding and managing extremes

IUSS
Scuola Universitaria Superiore Pavia

Motivation and Overview

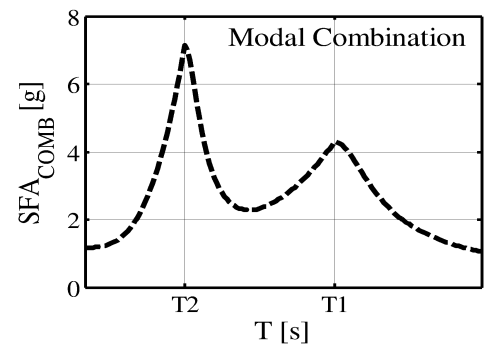
- A **modal superposition approach** is used to approximate the spectral floor acceleration (SFA) demands

- Current work builds on a previous framework proposed by Sullivan *et al.* [2013] (Nonlinear SDOF systems) and Calvi and Sullivan [2014] (Linear MDOF systems)

<u>Main Objectives to Extend Framework</u>

- Consider the effects of both primary and nonstructural damping ratio (**Peak Dynamic Amplification**)

- Incorporate effects of nonlinear response in the primary structure (**Modal Reduction Factors**)



Motivation and Overview

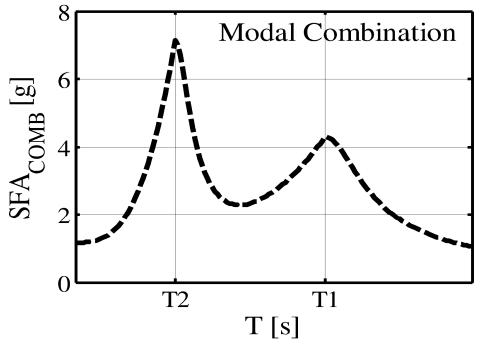
- A **modal superposition approach** is used to approximate the spectral floor acceleration (SFA) demands

- Current work builds on a previous framework proposed by Sullivan *et al.* [2013] (Nonlinear SDOF systems) and Calvi and Sullivan [2014] (Linear MDOF systems)

Main Objectives to Extend Framework

- Consider the effects of both primary and nonstructural damping ratio (**Peak Dynamic Amplification**)

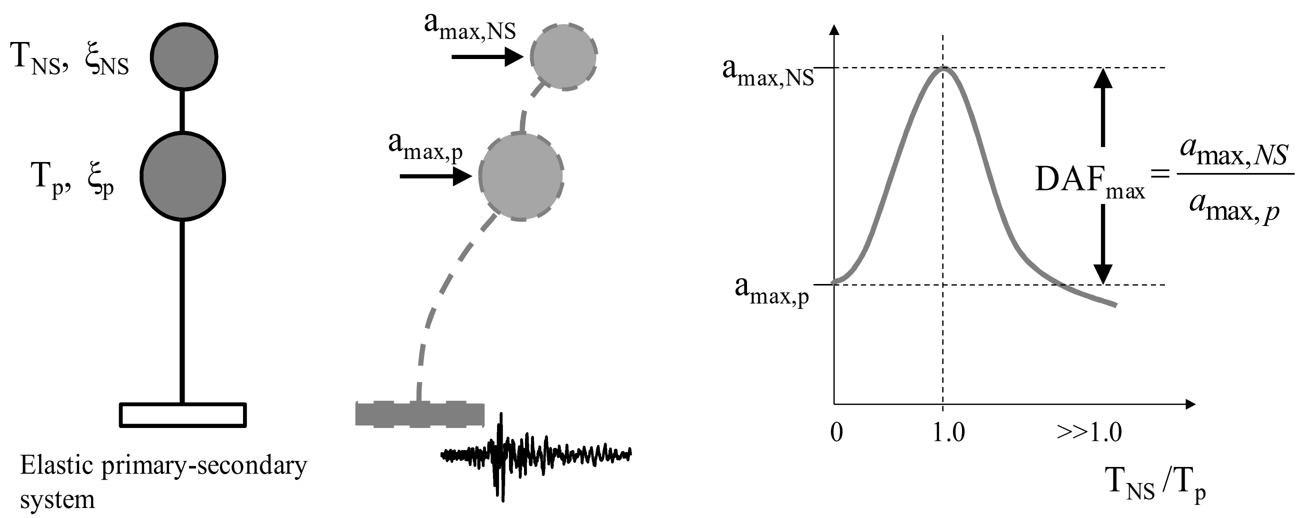
- Incorporate effects of nonlinear response in the primary structure (**Modal Reduction Factors**)



Current work will focus on quantifying the **amplification potential of moderate to long period structures** with significant second mode periods

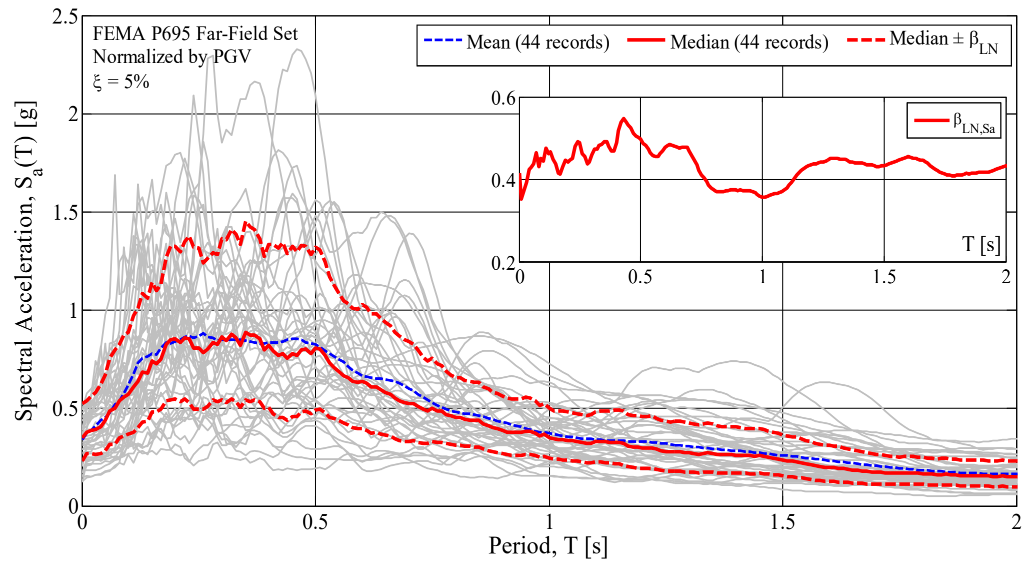
Peak Dynamic Amplification

- DAF_{max} is the amplification of a secondary elastic SDOF at the resonant condition ($T_p = T_{NS}$) with the primary elastic SDOF system
- Main focus is to investigate the effects of both primary and nonstructural damping ratios (Important for steel buildings commonly attributed damping less than 5%)



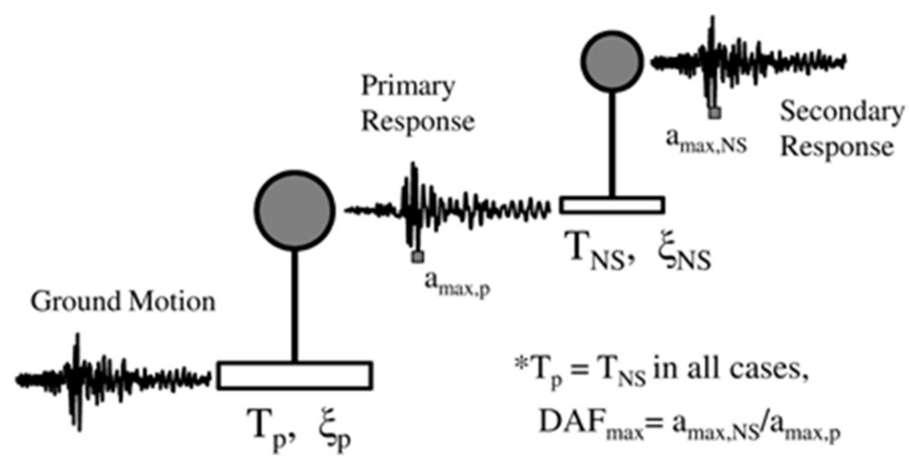
Peak Dynamic Amplification

- FEMA P695 far-field set [FEMA, 2009] is selected to represent seismic input
- 44 accelerograms total



<u>Primary-Secondary SDOF analysis</u>

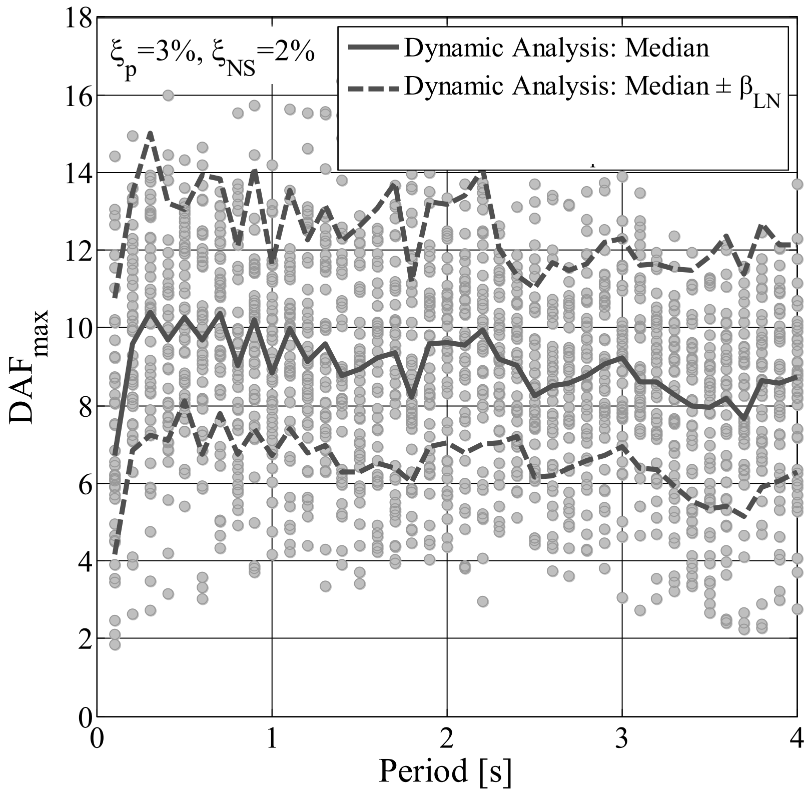
- T = 0.1s to 4.0s at 0.1s intervals
- Primary Damping (ξ_p)
  1%, 3% and 5%
- Non-Structural Damping (ξ_{NS})
  0.5%, 2%, 5% and 10%



Peak Dynamic Amplification

- "Amplification spectra" are produced (also recently used by Sullivan *et al.* 2013 and Vukobratović and Fajfar 2015)

- Regression analysis conducted from T_B = 0.3s to T= 4.0s using median data



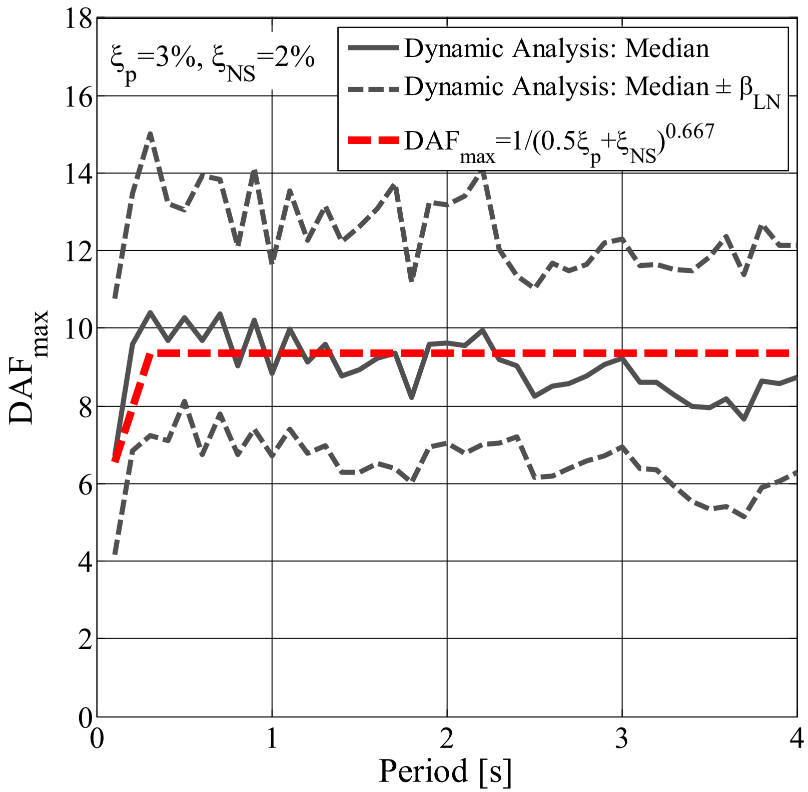
UME
understanding and managing extremes

IUSS
Scuola Universitaria Superiore Pavia

Peak Dynamic Amplification

$$DAF_{\max} = (a\xi_p + \xi_{NS})^b = \left(0.47\xi_p + \xi_{NS}\right)^{-0.661} \approx \left(0.5\xi_p + \xi_{NS}\right)^{-0.667}$$

$$DAF_{\max,\mathrm{T<T_B}} = DAF_{\max}\left(0.55 + 0.45\left(\frac{T}{T_B}\right)\right)$$



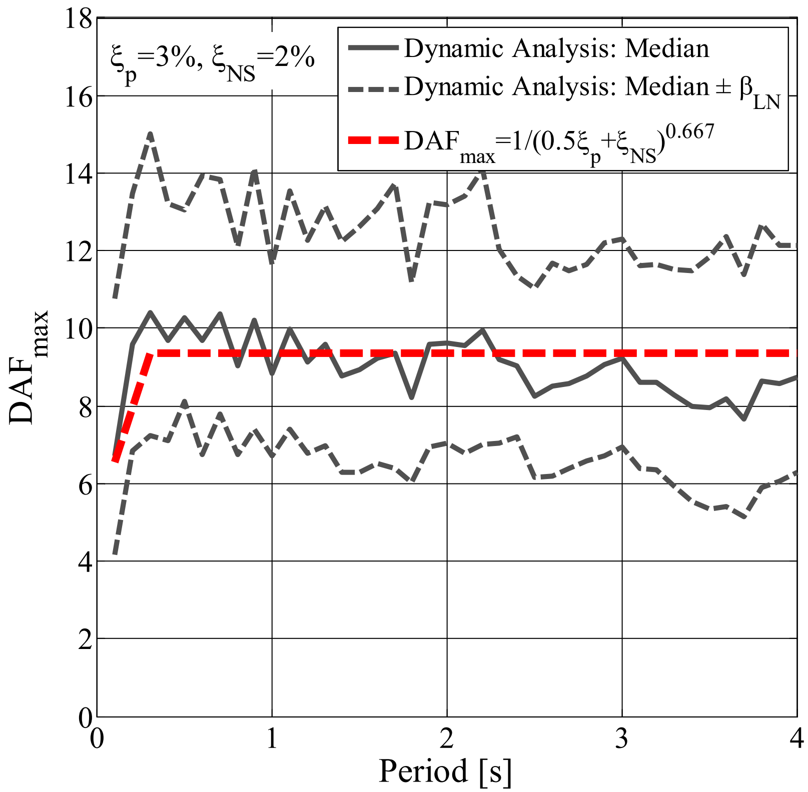
UME
understanding and managing extremes

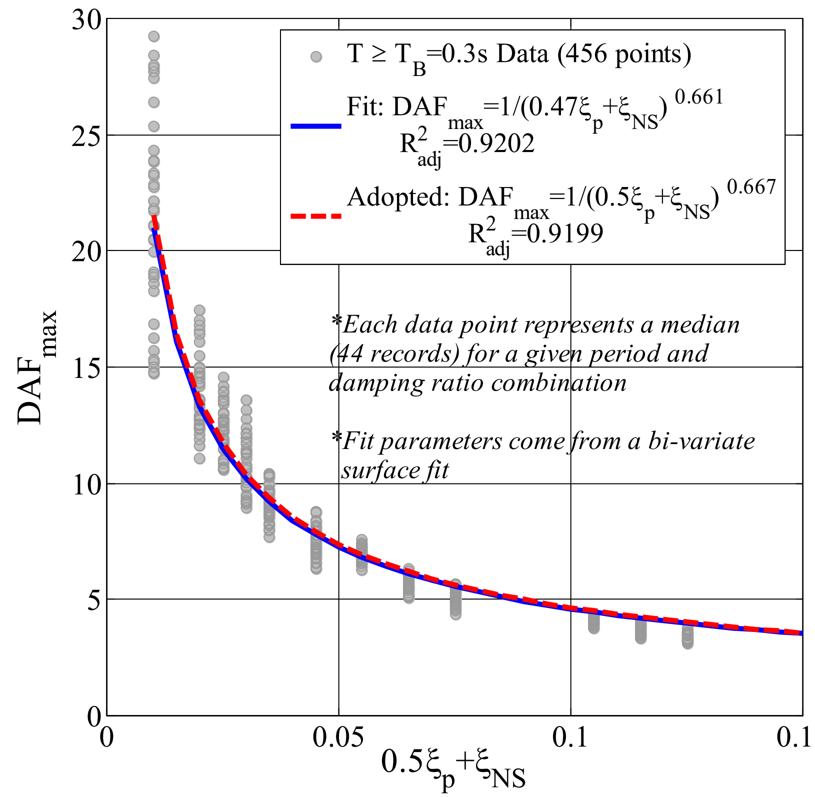
IUSS
Scuola Universitaria Superiore Pavia

Peak Dynamic Amplification

$$DAF_{\max} = (a\xi_p + \xi_{NS})^b = \left(0.47\xi_p + \xi_{NS}\right)^{-0.661} \approx \left(0.5\xi_p + \xi_{NS}\right)^{-0.667}$$

$$DAF_{\max,T<T_B} = DAF_{\max}\left(0.55 + 0.45\left(\frac{T}{T_B}\right)\right)$$



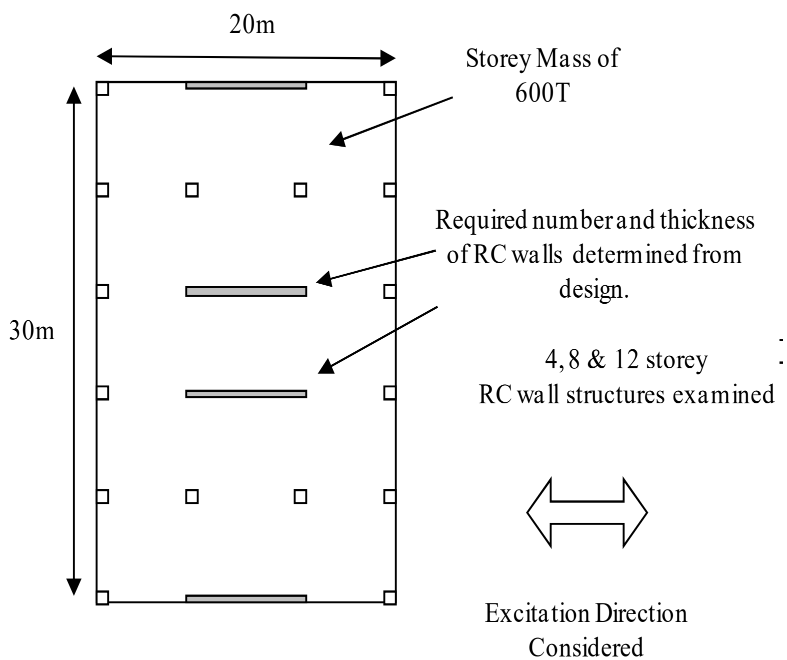


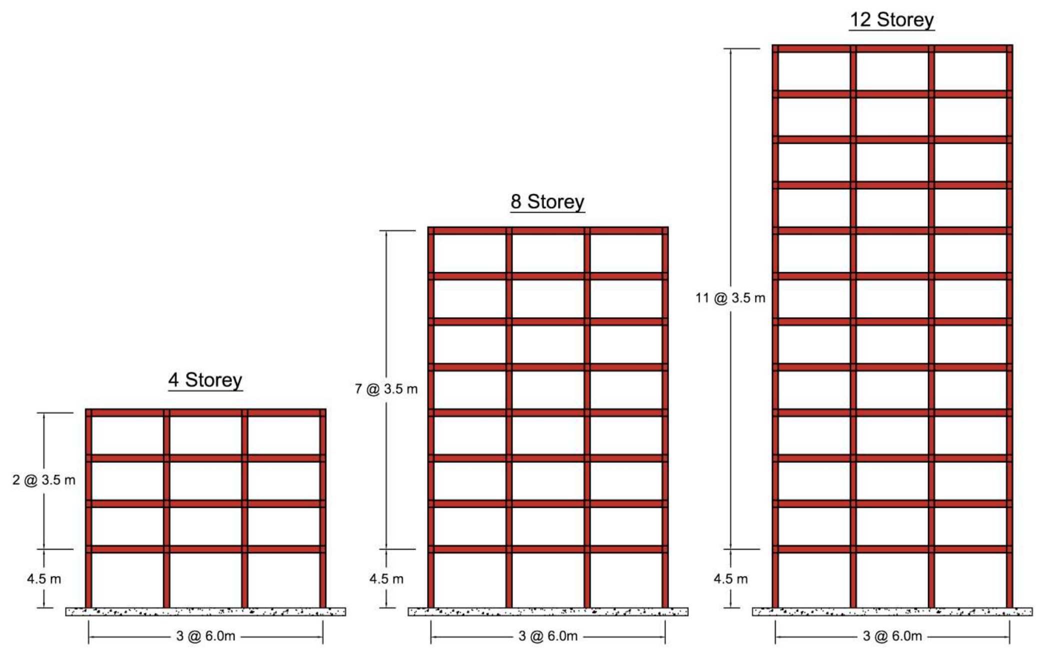
UME
understanding and managing extremes

IUSS
Scuola Universitaria Superiore Pavia

Analysis of MDOF Structures

- A total of **9 case study buildings** were studied
- **Three types**: RC cantilever walls, Stiff steel MRF, and Flexible steel MRF
- All three types consider **4, 8 and 12 storey variations**
- Buildings are modeled in 2D using lumped plasticity (Ruaumoko)



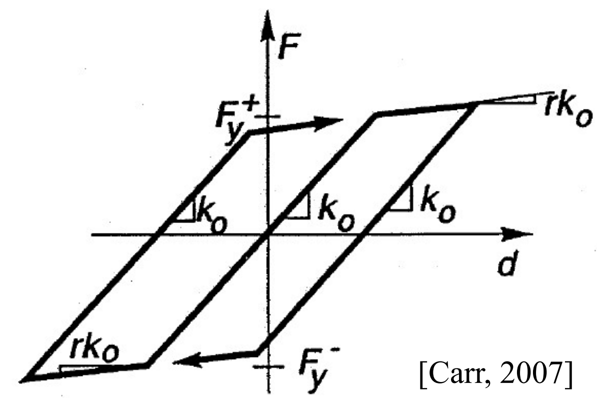


Analysis of MDOF Structures

Steel Moment-Resisting Frames

- Single 3 bay perimeter frame modeled
- Tributary mass from gravity columns considered
- **Bi-linear hysteresis** assumed for structural members
- 3% Tangent-stiffness proportional Rayleigh damping in the first two modes

Bi-Linear Hysteretic Model

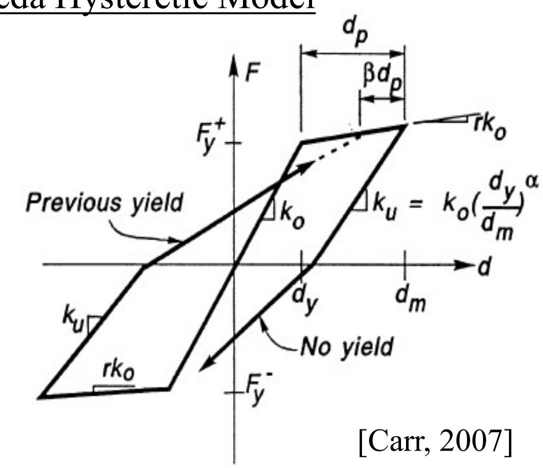


[Carr, 2007]

RC Cantilever Walls

- Equivalent cantilever ("stick model")
- **Nonlinearity only at the base**
- Base hinge assumes **"Takeda-Thin" hysteresis** using recommendations of Priestley *et al.* [2007]
- 5% Tangent-stiffness proportional Rayleigh damping in the first two modes

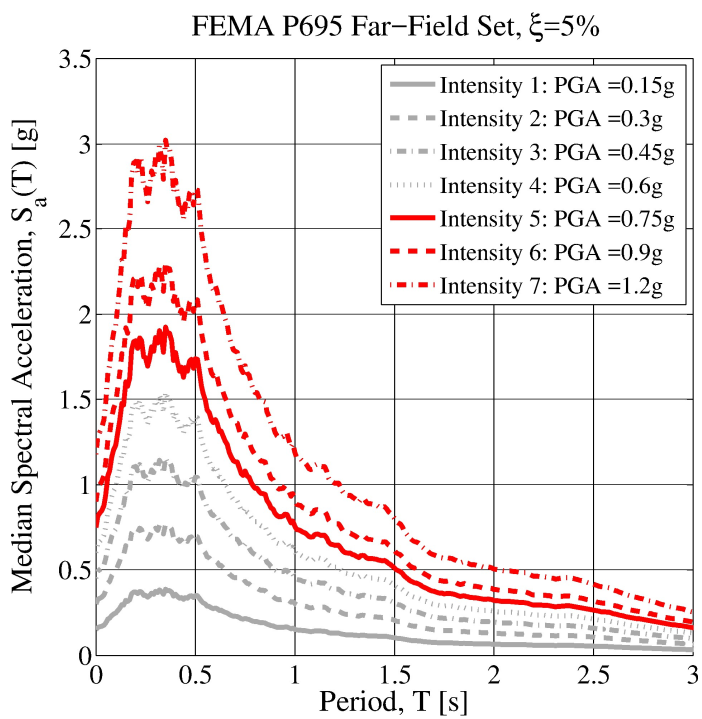
Takeda Hysteretic Model

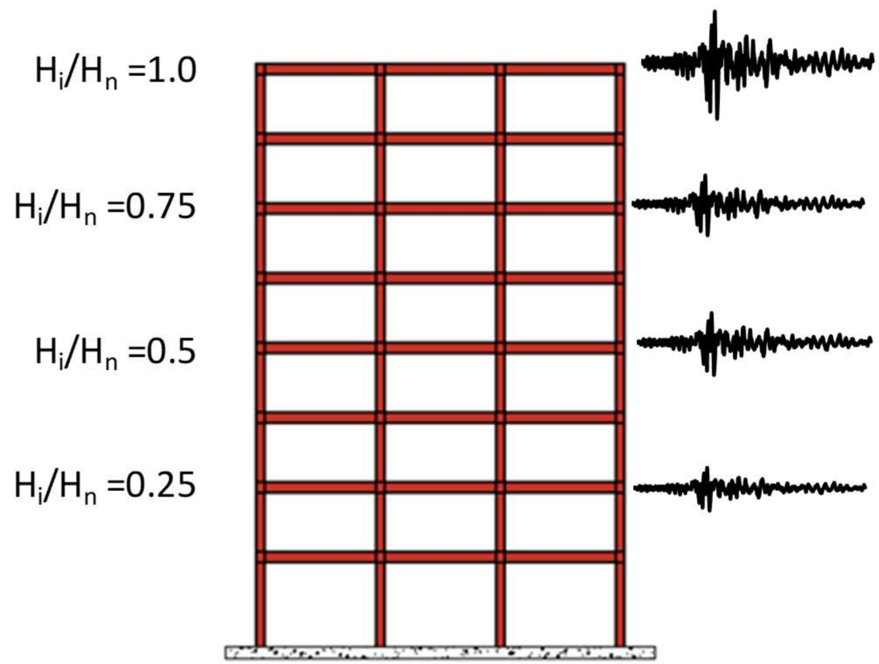


[Carr, 2007]

Analysis of MDOF Structures

- FEMA P695 far-field set [FEMA, 2009] was assumed for seismic input
- Seven intensity levels scaled by median PGA (0.15g to 1.2g)
- Case study buildings analyzed using nonlinear and elastic response
- Floor spectra produced at damping ratios of 0.5%, 2%, 5% and 10% of critical





Monitoring Ductility Demands

- Ductility demands are monitored on a record-by-record basis

•**RC Walls** assume the displacement ductility at the first mode effective height

$$\Delta_{y,i} = \frac{\varepsilon_y}{L_w} H_i^2 \left(1 - \frac{H_i}{3H_n}\right)$$

$$H_e = \frac{\sum_{i=1}^{n} m_i \Delta_i H_i}{\sum_{i=1}^{n} m_i \Delta_i}$$

•**Steel MRFs** use an estimated yield drift profile [Della Corte *et al.* 2014] and a work-done approach [Sullivan *et al.* 2010] to estimate system ductility

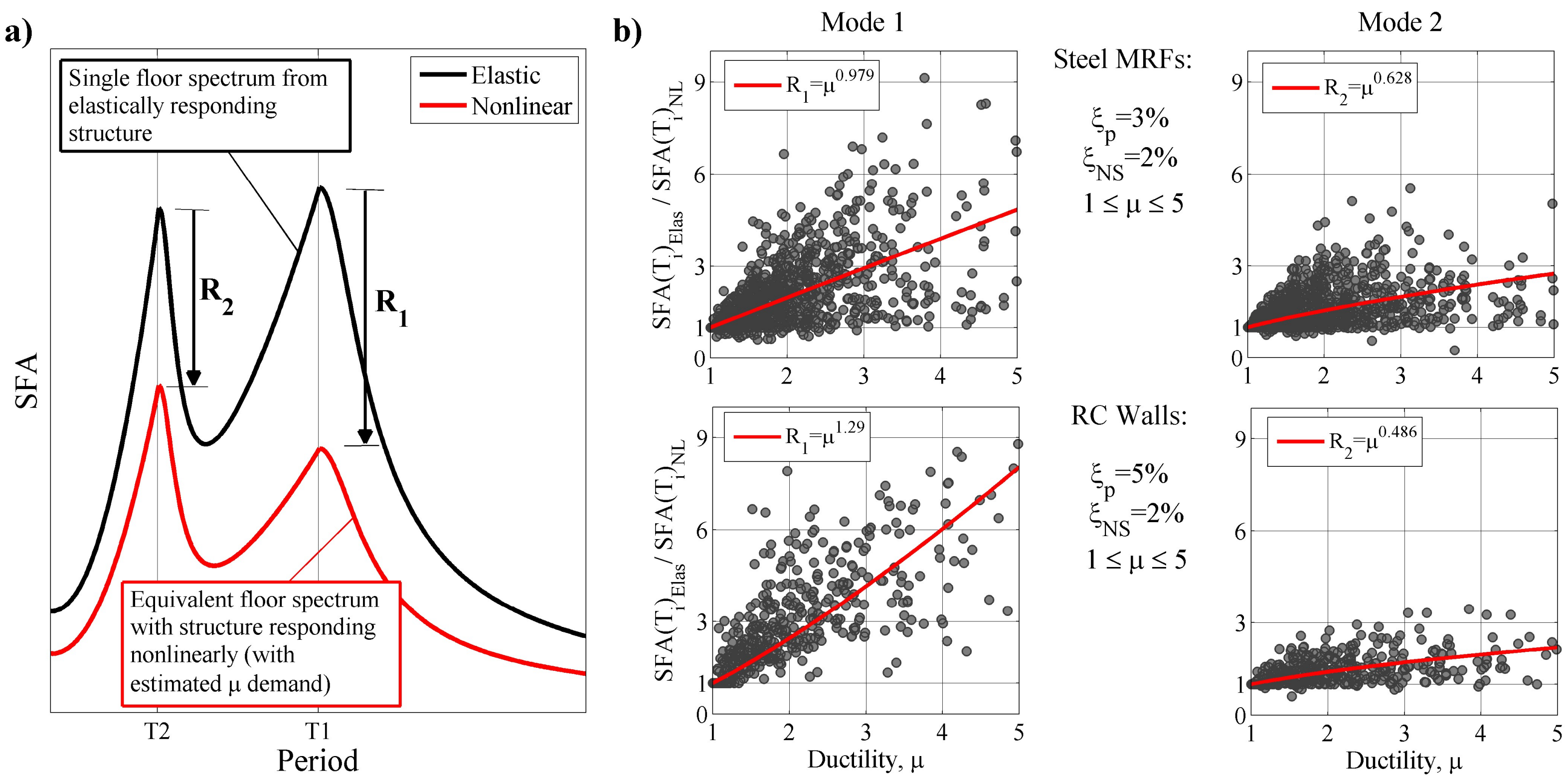
$$\theta_{y,j} = \frac{m_{j,R}\phi_{b,y}}{6}\left(\psi_{j,b} + \frac{1}{2}\frac{\beta I_b h}{I_c L_b}\right)$$

$$\mu_{\theta,i} = \frac{\theta_{d,i}}{\theta_{y,i}}$$

$$\mu = \frac{\sum_{i=1}^{n} V_i \theta_i \mu_{\theta,i}}{\sum_{i=1}^{n} V_i \theta_i}$$

Nonlinear Modal Reduction Factors

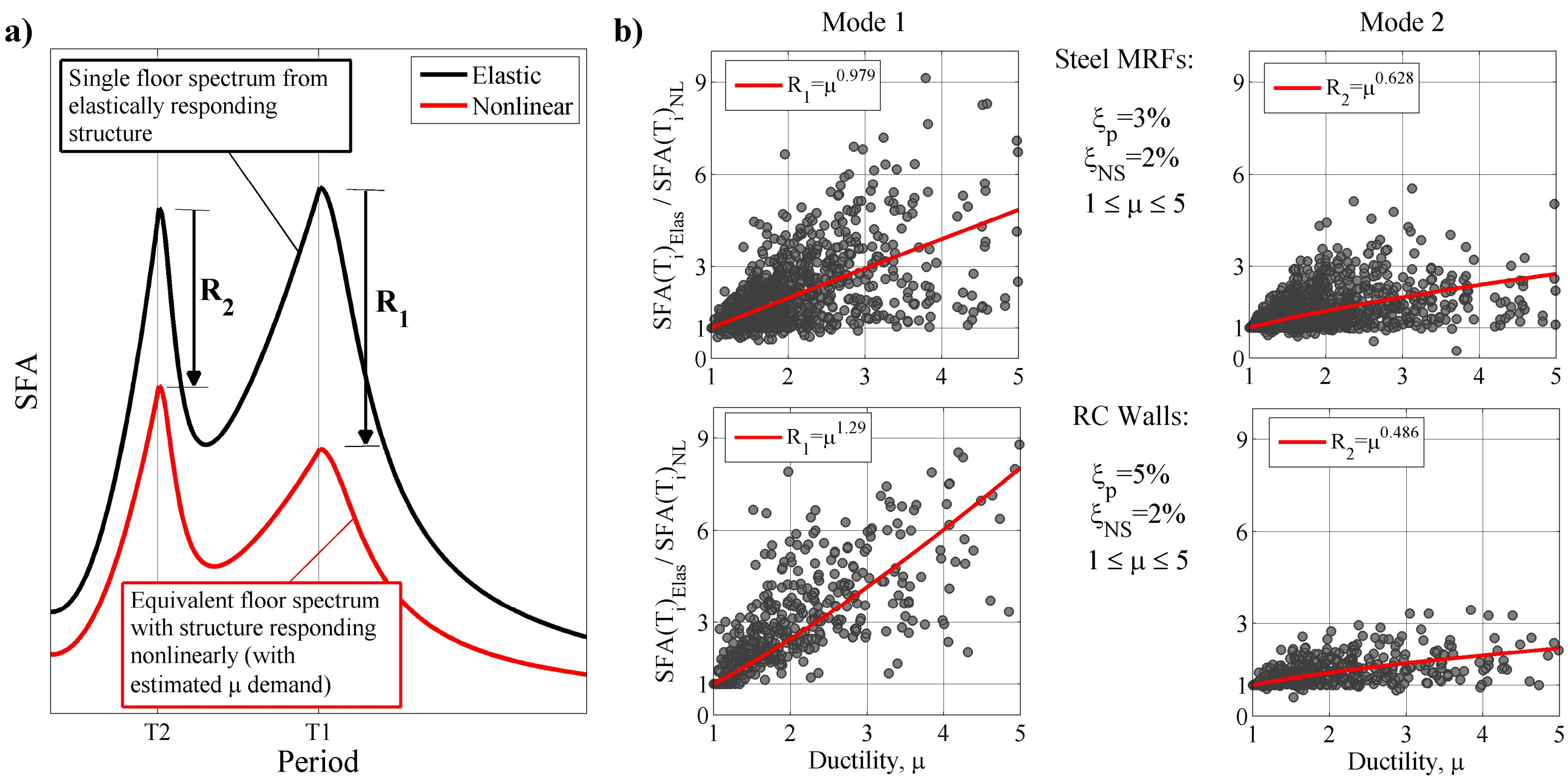
- Quantify the reduction in spectral peaks at modal periods due to non-linear demands (Roof level data assumed for generalized values)
- Represented using a simple **power law fit to the ductility demand** $R_i \approx \mu^{\alpha}$



Nonlinear Modal Reduction Factors

Fundamental Mode: $R_1 = R_{i=1} \approx \mu$ *Steel MRF* ; $R_1 = R_{i=1} \approx \mu^{1.25}$ *RC Wall*

All Higher Modes: $R_{HM} = R_{i>1} \approx \mu^{0.6}$ *Steel MRF*; $R_{HM} = R_{i>1} \approx \mu^{0.4}$ *RC Wall*



UME
understanding and managing extremes

IUSS
Scuola Universitaria Superiore Pavia

Summary of Approach

- Define target acceleration spectrum, modal properties and ductility demand
- For each mode i and DOF j , the modal floor acceleration must be estimated

$$a_{\max,j,i} = \phi_{j,i}\Gamma_i\left(\frac{S_a(T_i)}{R_i}\right)$$

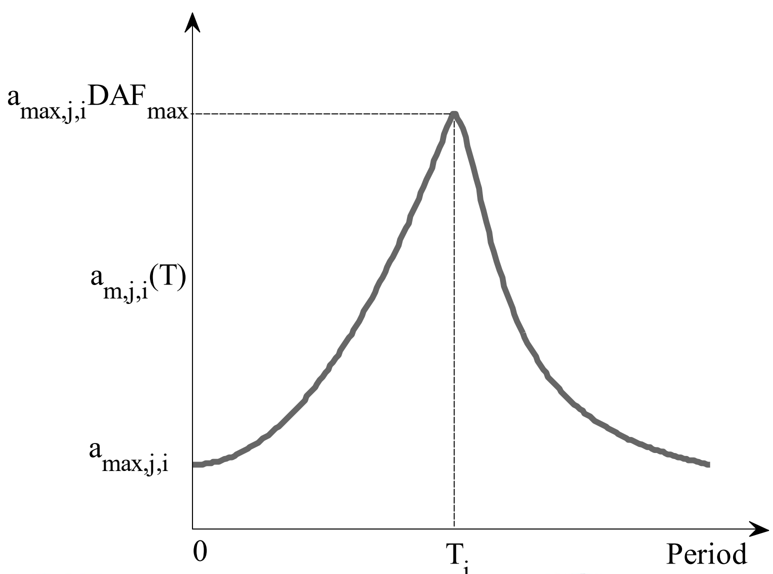
- Then, individual modal contributions can be estimated

$$DAF_{\max} = \left(0.5\xi_p + \xi_{NS}\right)^{-0.667}$$

$$a_{m,j,i}\left(T < T_i\right) = \left(T/T_i\right)^2\left[a_{\max,j,i}\left(DAF_{\max} - 1\right)\right] + a_{\max,j,i}$$

$$a_{m,j,i}\left(T_i \le T \le T_{i,e}\right) = a_{\max,j,i}DAF_{\max}$$

$$a_{m,j,i}\left(T > T_{i,e}\right) = a_{\max,j,i}\left[\left(1 - \frac{T}{T_{i,e}}\right)^2 + \left(0.5\xi_p + \xi_{NS}\right)\right]^{-0.667}$$



Summary of Approach

- **Period elongation** of modal peak region considered for **RC walls** in modes 1 and 2

$$T_{1,eff} = T_1 \sqrt{\frac{\mu}{\left(1 + r\left(\mu - 1\right)\right)}}$$

$$T_{2,eff} = T_2 \left(1 + 0.5\left(\frac{\mu}{\mu_{pin}}\right)\right) \quad for \quad 1.0 < \mu \le \mu_{pin}$$

$$\mu_{pin} \approx 5.0$$

- All modal contributions are combined with the SRSS rule

$$SFA_j\left(T\right)_{SRSS} = \sqrt{\sum_{i=1}^{nm} a_{m,j,i}(T)^2}$$

*nm = 3 for RC Walls, 4 for steel MRFs

Summary of Approach

- **Rigid mode response of RC walls** are approximated by taking the **envelope of the ground motion spectrum** (at ξ_{NS}) and the SRSS estimate **below mid-height** (Based on original assumption made by Calvi and Sullivan [2014])

$$SFA_j(T)_{RC\ Walls} = \begin{cases} \max\left(SFA_j(T)_{SRSS}, S_{a,GM}(T,\xi_{NS})\right) & for\ H_i/H_n < 0.5 \\ SFA_j(T)_{SRSS} & for\ H_i/H_n \geq 0.5 \end{cases}$$

Summary of Approach

- **Rigid mode response of RC walls** are approximated by taking the **envelope of the ground motion spectrum** (at ξ_{NS}) and the SRSS estimate **below mid-height** (Based on original assumption made by Calvi and Sullivan [2014])

$$SFA_j(T)_{RC\ Walls} = \begin{cases} \max\left(SFA_j(T)_{SRSS}, S_{a,GM}(T,\xi_{NS})\right) & for\ \ H_i/H_n < 0.5 \\ SFA_j(T)_{SRSS} & for\ \ H_i/H_n \geq 0.5 \end{cases}$$

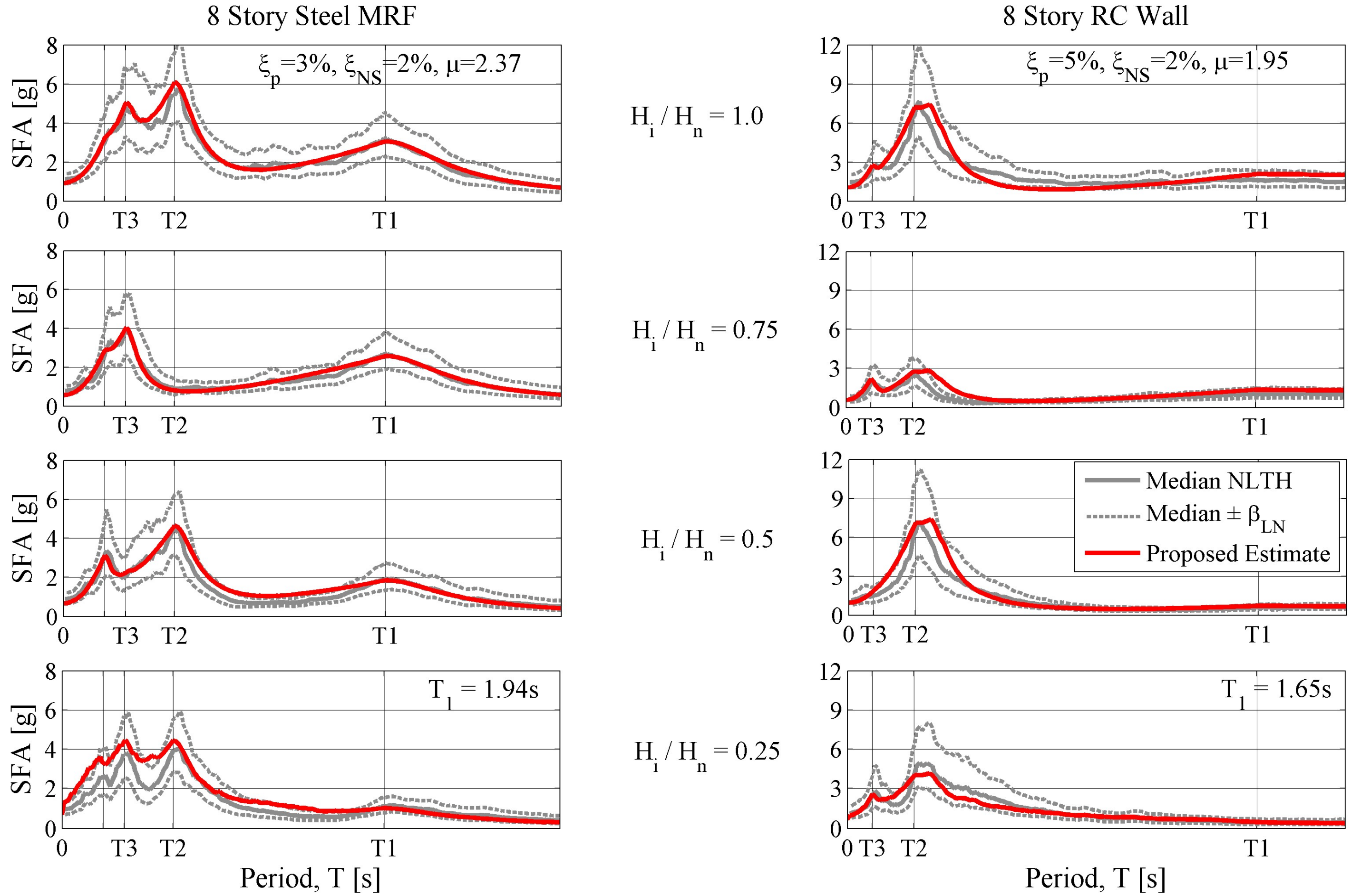
- **Steel MRFs** are **adjusted for peak floor acceleration** (PFA) **considering reduction in modes 1 and 2 only**

$$PFA_{j,Steel\ MRF} = \left[\sum_{i=1}^{2}\left(a_{\max,j,i}\right)^2 + \sum_{i=3}^{nm}\left(a_{\max,j,i}R_i\right)^2\right]^{0.5}$$

$$SFA_j(T)_{Steel\ MRF} = \begin{cases} \max\left(SFA_j(T)_{SRSS}, PFA_j(T)\right) & for\ \ 0 \leq T \leq T_{nm} \\ SFA_j(T)_{SRSS} & for\ \ T > T_{nm} \end{cases}$$

Comparing with Median NLTH Results

- Highest intensity at ξ_{NS} = 2%



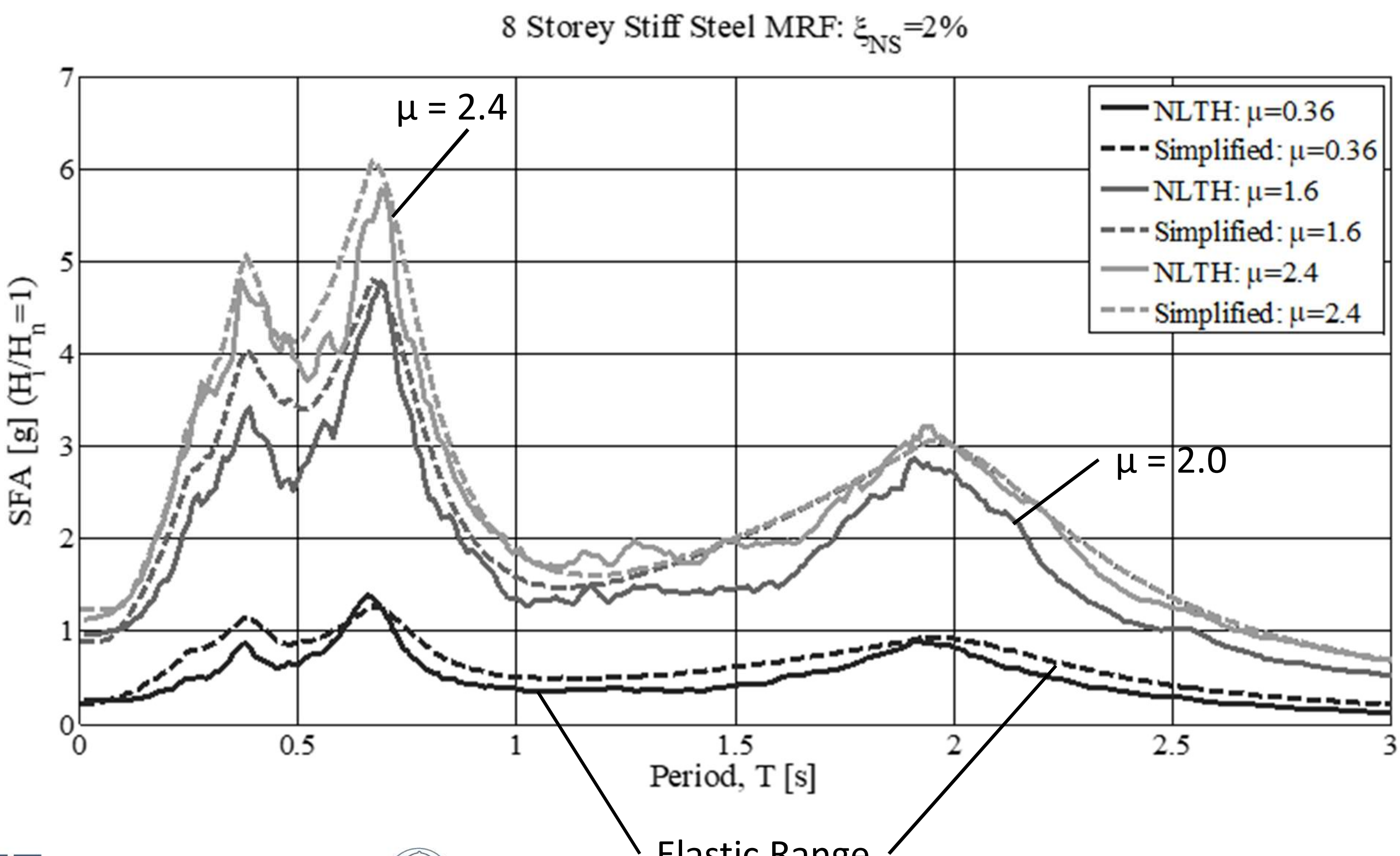
UME
understanding and managing extremes

IUSS
Scuola Universitaria Superiore Pavia

Comparing with Median NLTH Results

- Range of intensities with ξ_{NS} = 2% at **roof level**

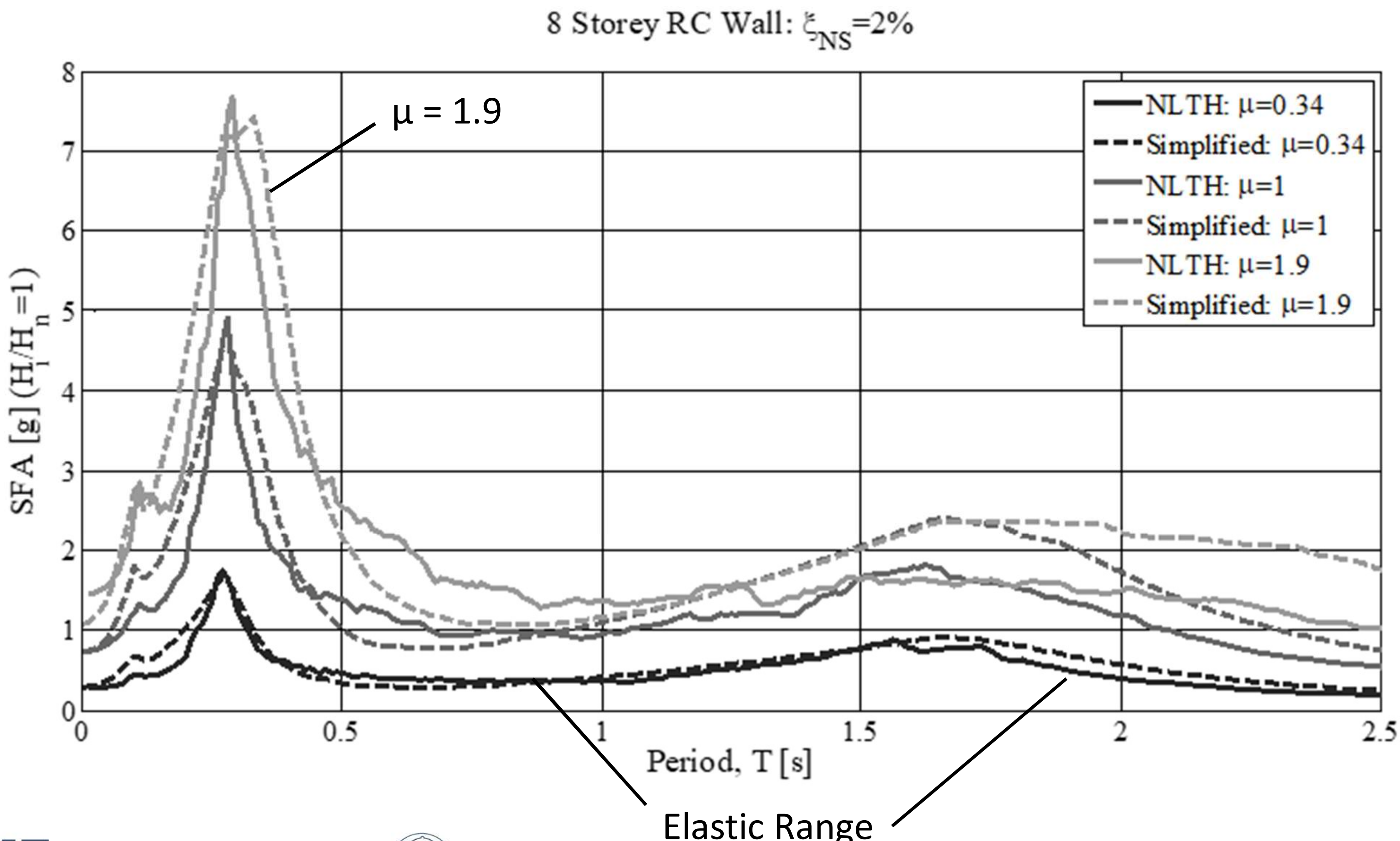
8 Storey Steel MRF



Comparing with Median NLTH Results

- Range of intensities with ξ_{NS} = 2% at **roof level**

8 Storey RC Wall



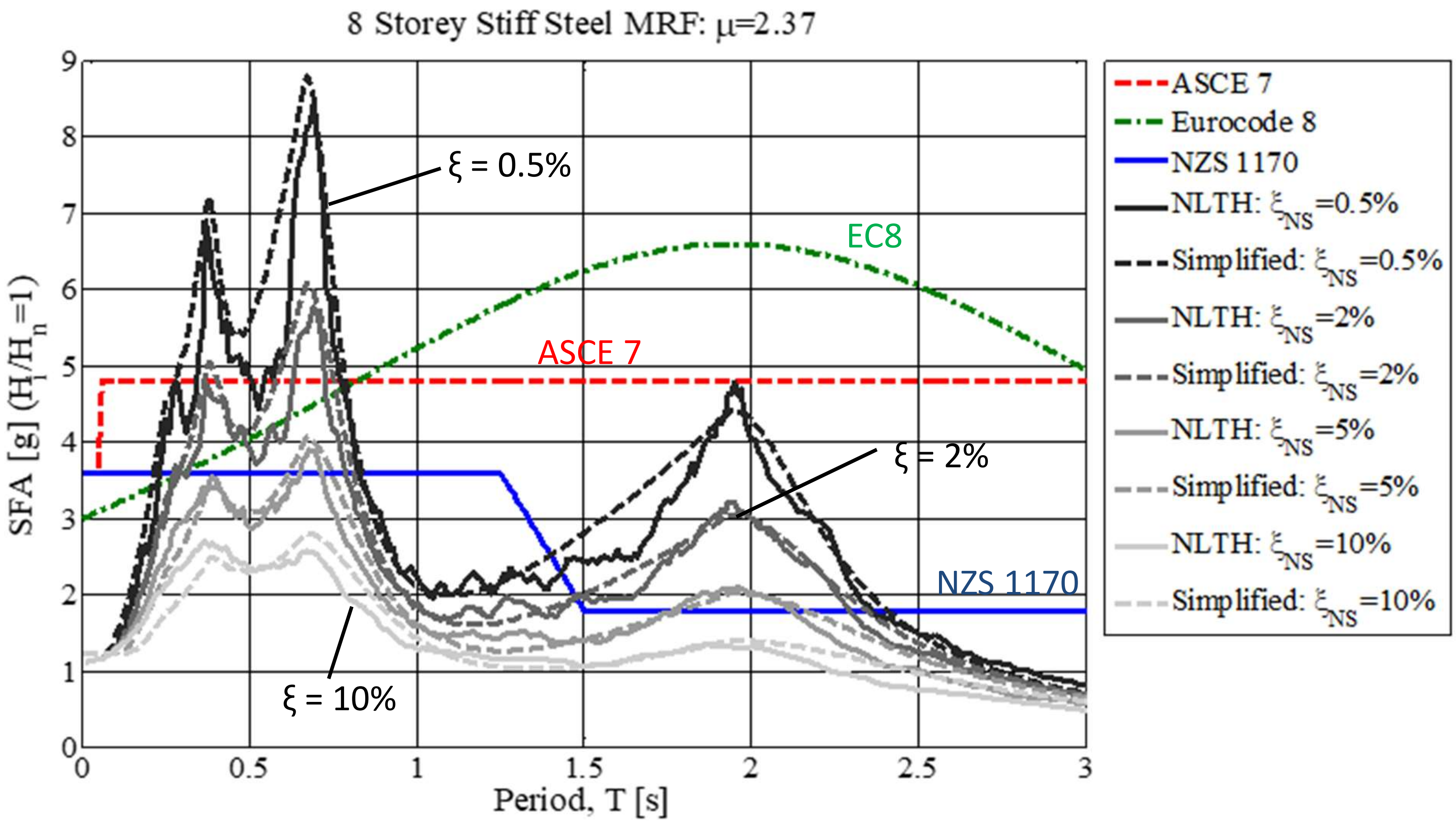
UME
understanding and managing extremes

IUSS Scuola Universitaria Superiore Pavia

Comparing with Median NLTH Results

- **All values of ξ_{NS}** at highest intensity (roof level)

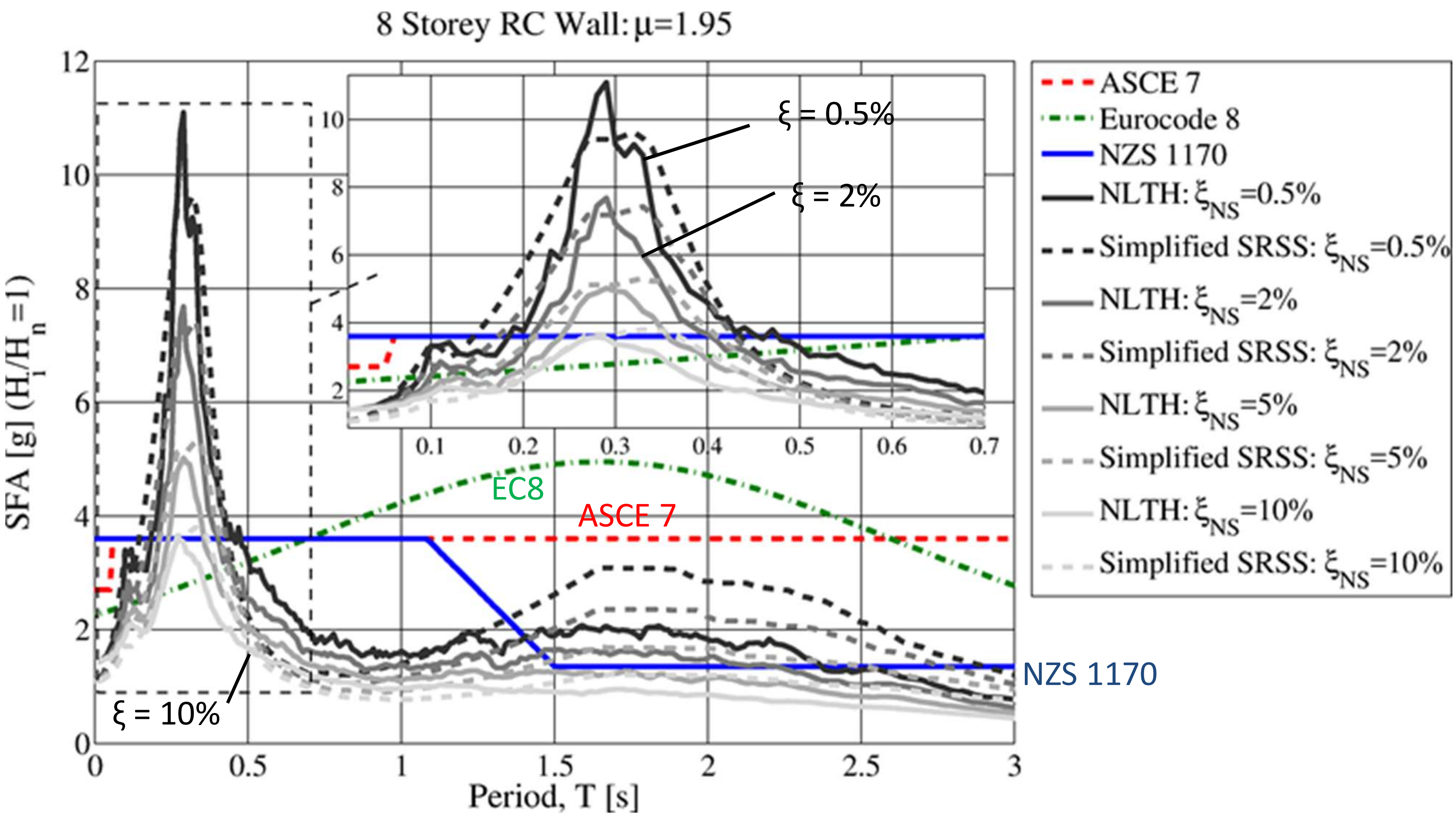
8 Storey Steel MRF



Comparing with Median NLTH Results

- **All values of ξ_{NS}** at highest intensity (roof level)

8 Storey RC Wall



Concluding Remarks

- A modal superposition approach to estimate spectral floor acceleration demands in nonlinear MDOF structures has been presented
- The approach is shown to give similar feedback in terms of amplification potential of structures when comparing to dynamic time history methods
- Important factors such as damping ratio, level of ductility demand, and structural type are accounted for while maintaining a practical level of simplicity

Concluding Remarks

- A modal superposition approach to estimate spectral floor acceleration demands in nonlinear MDOF structures has been presented
- The approach is shown to give similar feedback in terms of amplification potential of structures when comparing to dynamic time history methods
- Important factors such as damping ratio, level of ductility demand, and structural type are accounted for while maintaining a practical level of simplicity

Ongoing and Future Research

- Refined consideration of modal reduction factors
- More explicit considerations of peak floor accelerations
- Extension to reinforced concrete frame structures
- Considerations for uncertainties in modal properties and record to record variability (dispersion)

Thank you for your attention!