Vertical Distribution of Force-Controlled Seismic Responses in Multi-Story RC Buildings

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Introduction and Background

- Recent shake table tests and EQ simulations have indicated that design diaphragm and shear forces calculated with ASCE 7-10 and 16 are too low.

- Inelasticity can have a significant impact on the forces associated with the 1st mode type of response, but likely not on the higher modes.

- Both ELF and RSA methods assume inelasticity to have the same impact at all modes (same R factor), is that true?
Introduction and Background

Equivalent Lateral Force (ELF) Method

Design Lateral Forces
- $F_u = F_{cl} / R$
- Elastic
- Reduced

Design Story-Moments
- $M_u = M_{cl} / R$

Design Story-Shears
- $V_u = V_{cl} / R$

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Introduction and Background

Response Spectrum Analysis (RSA) Method

\[ F_{el,1} + F_{u,1} + F_{el,2} + F_{u,2} + F_{el,3} + F_{u,3} + \ldots = \text{Total} \]

\[ V_u = \frac{V_{el}}{R} \]

\[ M_u = \frac{M_{el}}{R} \]
Introduction and Background

Inelastic Modal Lateral Force Distribution

\[ \text{heff, in} \times \text{Min} > \mu \times \text{Vin} > \mu \times \text{Vu} \]

\[ \text{Fin} < \text{heff, el} \]

\[ \text{Elastic} \]

\[ \text{Inelastic} \]

\[ F_{u,1} = F_{el,1} / R \]

\[ F_{u,2} \sim F_{el,2} \]

\[ F_{u,3} \sim F_{el,3} / R \]

\[ \text{Mode-1} + \text{Mode-2} + \text{Mode-3} + \ldots = \text{Total} \]

\[ V_{in} > V_u \]

\[ M_{in} > M_u \]
ASCE 7-10 and 7-16 Provisions

- This inelastic behavior on higher modes has not been addressed in ASCE 7-10
- However, ASCE 7-16 addresses it for diaphragm design but does not require it
OpenSees Shear Wall Model

- Walls: Distributed plasticity FBBC elements
- Shear softening: Effective shear stiffness (0.10G)
- $L_p$: calculated by equation, assigned to the base IP
- Tensile reinforcing bar rupture: the rupture strain
- Buckling of longitudinal bars: implicitly modeled
OpenSees Shear Wall Model Capabilities

Test results from Dazio et al., 2009
Description of 12-Story Shear Wall Building

- Designed with ELF
- For a generic site with $S_s=1.5g$ and $S_1=0.6g$
- Dimensions, details and specified material properties for the building components comply with ASCE 7-10 and ACI 318 requirements
PEER NGA West-2

Ground Motion Dataset

Magnitude, M

PSA/PGA

Period, sec

PSA/PGA

Magnitude, M
Selection of 50 far-field ground motions
PCA (Principle Component Analysis) is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components.

Often used to visualize genetic distance and relatedness between populations.
Modal Decomposition Technique Using Fourier Transform

- Useful to understand the nature of seismic demands
- Conduct Fourier-based filtering of response
- Period ranges are specified as bandpass frequencies, considering the transition of modes

Fourier Transform of \( x(t) \):

\[
X(\tau, \omega) = \int x(t) \omega(t - \tau) e^{-i\omega t} dt
\]

5-second time intervals are used in the decomposition method for filtering
Modal Decomposition of Base Shear Demands

![Modal Decomposition Using Fourier Transform](image)
Modal Decomposition Using Fourier Transform

Modal Decomposition of Base Shear Demands

Energy content in each mode is confined to corresponding frequencies.
Instantaneous Shear Forces For EQ1

Modal Decomposition Using Fourier Transform

Relative Height

\[ \frac{V}{V_{bu}} \]

EQ
Mode-1
Mode-2
Mode-3
Modes 1+2+3

\[ t = 2.83 \text{ sec} \]
\[ t = 14.3 \text{ sec} \]
\[ t = 14.81 \text{ sec} \]
\[ t = 15.43 \text{ sec} \]
Effective Modal Earthquake (Elastic) Force Distributions

\[ m \ddot{x} + c \dot{x} + k x = -m \ddot{t} \dot{x}_g \]

\[ m \ddot{t} = \sum_{n=1}^{N} s_n = \sum_{n=1}^{N} \Gamma_n m \phi_n \]

\[ s_n = \Gamma_n m \phi_n \]

Using a modified version of OpenSees that enables assigning

\[ t = s_n \]

Under \(-m s_n \ddot{x}_g\)
Comparison to Nonlinear Modal Time History Analysis (NMTHA)

Elastic Modal Demands

Diaphragm Forces

Shears

Moments

Inter-story Drifts

Fourier matches very well to LMTHA
Comparison to Nonlinear Modal Time History Analysis (NMTHA)

Inelastic Modal Demands

Diaphragm Forces

Moments

Shears

Inter-story Drifts

Fourier matches the total response better than NMTHA
Modal Demands Using Fourier-Based Method

12-Story Building

Diaphragm Forces

Shears

Moments

Inter-story Drifts

Relative Height

F_i / F_i, des-ELF

V_i / V_i, des-ELF

M_i / M_i, des-ELF

IDR_i (%)
Conclusion

- A Fourier-based method was found to adequately decompose the response into modal components.

- Shears and diaphragm forces are largely controlled by higher modes, indicating low R factors for higher modes.

- The large difference in the NTHA and design demands stems largely from the significant higher mode contributions for diaphragm forces and shears.
Thank you!

Thanks!