Symposium Celebrating the Career of

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Seismic Shear Force Amplification in Frame–Wall Systems

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For walls where $H_w/l_w \geq 2$ the design shear force considered for **design of horizontal reinforcement the shear force V_e** shall be calculated using the expression

$$V_e = \beta_v \frac{(M_p)_t}{(M_d)_t} V_d$$

V_d = calculated shear force

Except for the case where the entire design shear force is resisted by the walls β_v = 1.5. Otherwise β_v = 1.0 shall be used.

$(M_p)_t$ = moment capacity at the base calculated using characteristic material strengths, considering strain hardening. Unless advanced models are used $(M_p)_t = 1.25\ (M_r)_t$ where $(M_r)_t$ = moment capacity based on design material strengths.

$(M_d)_t$ = design moment at the base calculated using factored horizontal and vertical loads.

Equation is different from its 2007 predecessor in national code.

This Equation Begs Several Questions.

- It is too general, and ignores variability of dynamic effects.
- It runs contrary to parameters used in other more representative studies
- The dynamic amplification factor has not been fully calibrated by realistic models.
- Its applicability of medium-height buildings (4 – 12 stories tall) has not been fully assessed.

Other Current Expressions

- New Zealand Code 3101 (NZS 3101, 2006):

$$\beta_v = 0.9 + N/10 \quad \leq 1.8 \qquad N \leq 6$$

$$\beta_v = 1.3 + N/30 \quad \leq 1.8 \qquad N > 6$$

N = number of stories. But applies when $N < 15$.

- EC8 (2005) uses the expression developed by Keintzel (1990):

$V_{Ed} = \varepsilon V'_{Ed}$ $$\varepsilon = q\sqrt{\left(\frac{\gamma_{Rd}}{q}\cdot\frac{M_{Rd}}{M_{Ed}}\right)^2 + 0.1\cdot\left(\frac{S_e(T_c)}{S_e(T_1)}\right)^2} \leq q, \text{ but } \varepsilon > 1.5$$

γ_{Rd} = 1.2 on account of capacity increase due to strain hardening, M_{Rd} = actual moment capacity, M_{Ed} = design moment, T_1 = building fundamental period, T_c = spectrum corner period and $S_e(T)$ = elastic response spectrum ordinate, q = behavior factor = R/Ω.

EC8 notation:

$$V_e = \varepsilon V_d$$

Presumably T_1 reflects effect of amount of walls.

Three Principal Features of Framework for Parametric Investigation:

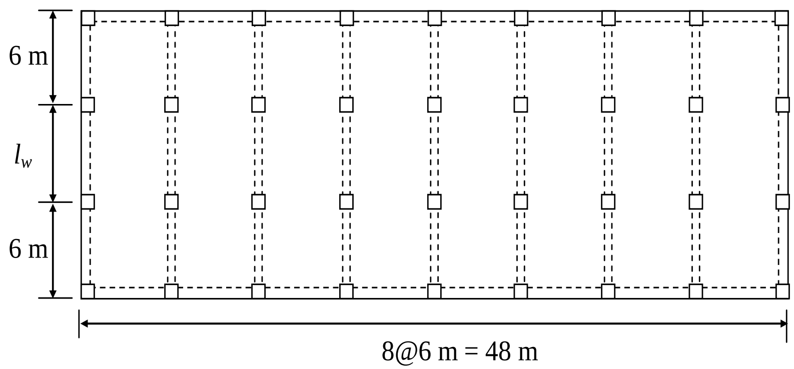
- Simplified single wall, equivalent frame model for use in the time domain.
- Revert to a continuous differential equation solution for expressing the stiffness and strength of the frames along with their dynamic properties.
- Examine the statistics of the dynamic shear force amplification by comparing the design capacity and seismic demand for different wall design parameters and ratios.

Analytic framework for the parametric investigation:

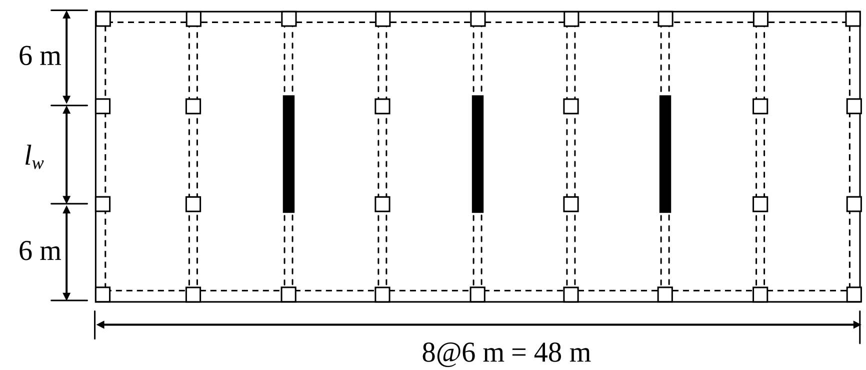
- Number of stories: 4, 8, 12 story tall wall-frame systems
- Wall width L_w: 3 m, 5 m and 8 m
- Wall ratio, *p defined as*

$$p = \frac{total\ wall\ area\ in\ a\ given\ principal\ direction}{building\ plan\ area}$$

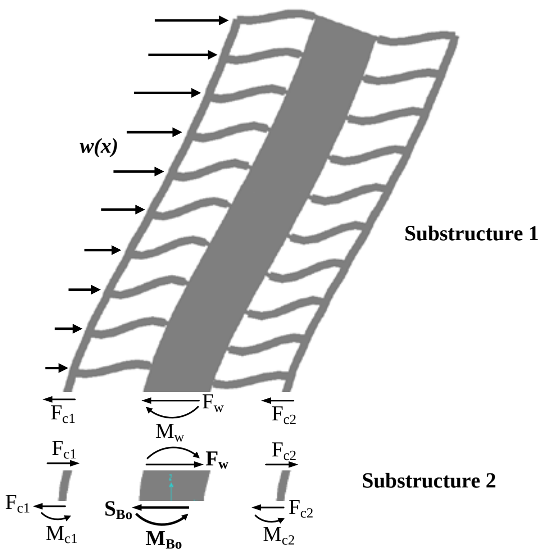
Parametric framework for analysis:

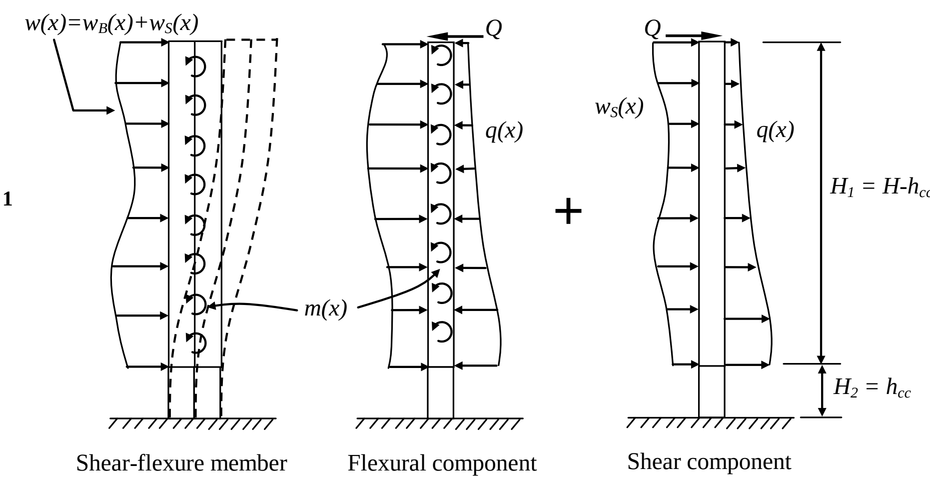


Representative frame system



Wall-frame system





$$\frac{d^4y}{dx^4} - \alpha^2 \frac{d^2y}{dx^2} = \frac{w(x)}{EI}$$

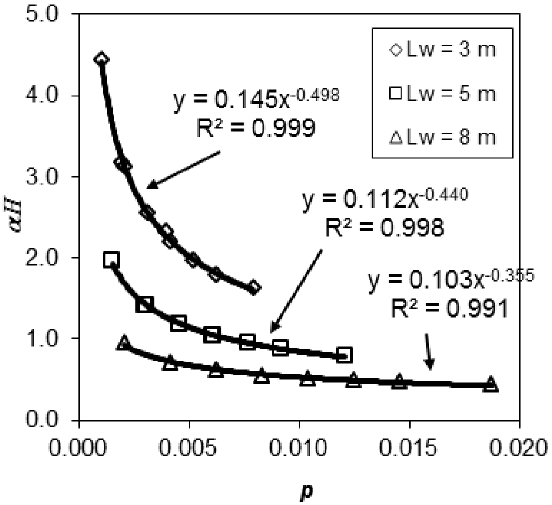
$$\alpha^2 = \frac{GA+\eta}{EI}$$

Kazaz and Gülkan (2012)

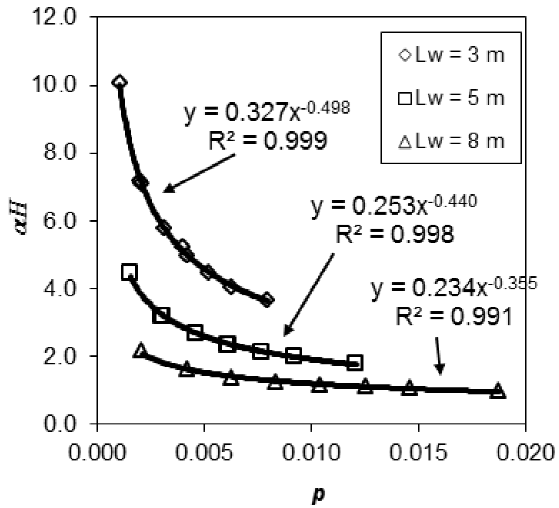
Parametric framework for analysis:

Wall ratio ρ vs αH from models

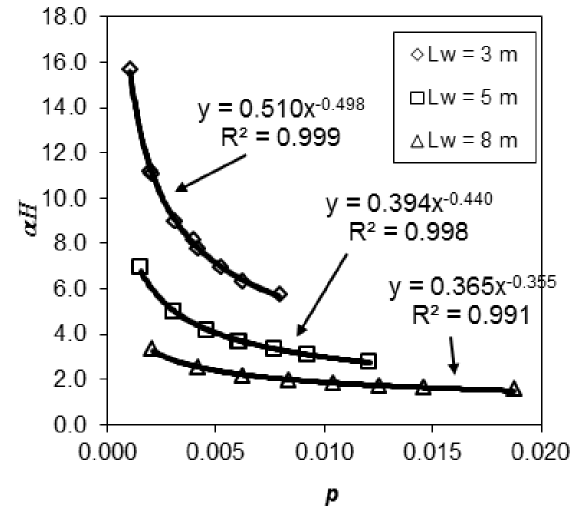
4-story



8-story



12-story



First mode vibration period:

$$T = 0.00406 \frac{H_w}{L_w} N \frac{1}{\sqrt{p\left(1.875^2 + (\alpha H)^2\right)}}$$

Kazaz and Yakut (2010)

Parametric framework for analysis:

$$M_{Bo} = \frac{\frac{V_t \sinh(\alpha H_1)}{\alpha} - \frac{V_t h_{cc}^4}{3EI_c f}\left[\frac{\alpha h_{cc} \sinh(\alpha H_1)}{2} + \cosh(\alpha H_1)\right] - \frac{w_1}{\alpha^3 H}\left[\alpha h_{cc} \cosh(\alpha H_1) + \sinh(\alpha H_1) - \alpha H\right]}{\left(1 - \frac{h_{cc}^3}{4EI_w f}\right)\alpha h_{cc} \sinh(\alpha H_1) + \left(1 - \frac{h_{cc}^3}{2EI_w f}\right)\cosh(\alpha H_1)}$$

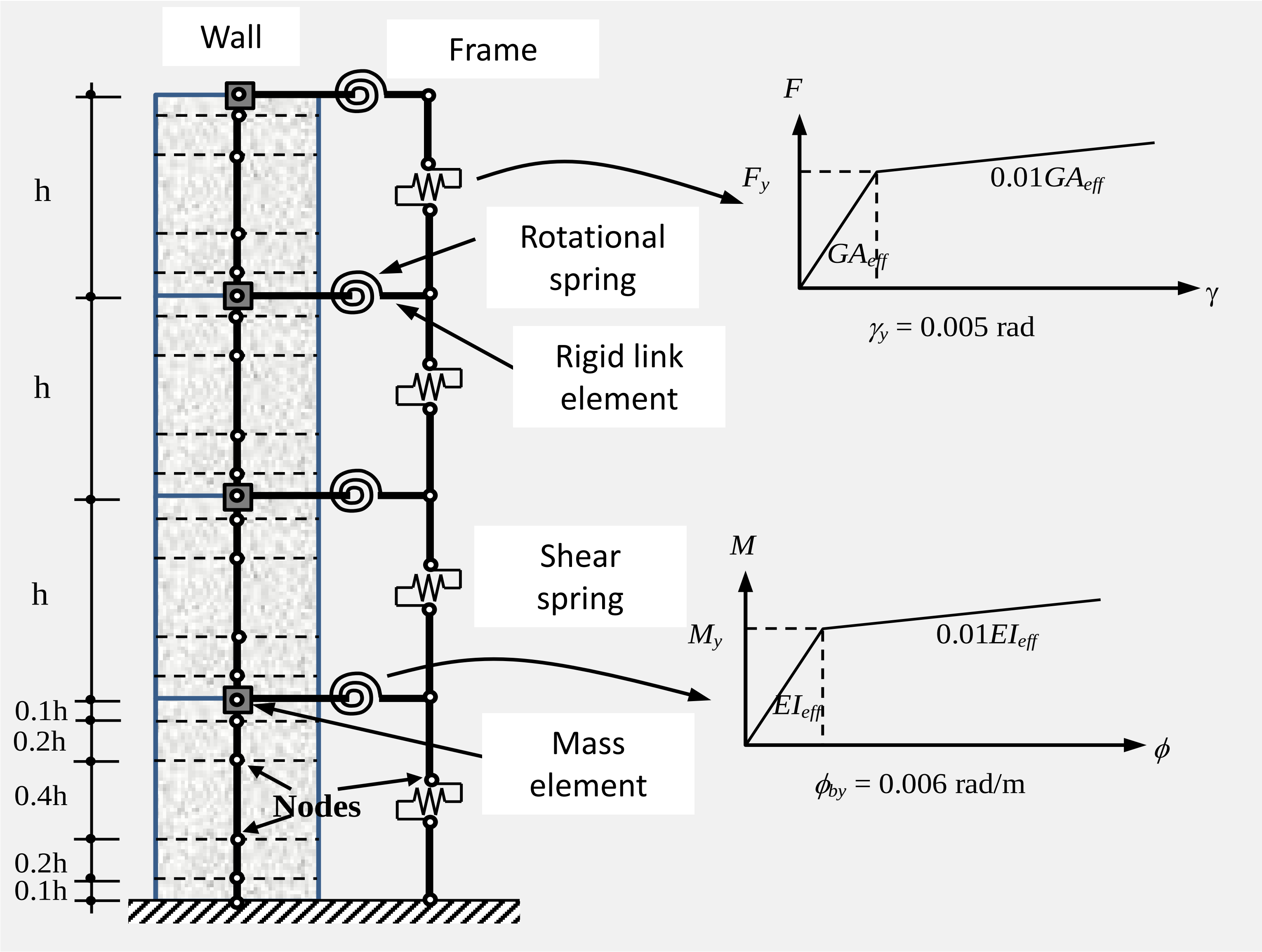
$$V_w = M_{Bo} \frac{h_{cc}^2}{2 fEI_w} - V_t \frac{h_{cc}^3}{3 fEI_c}$$

$$f = \frac{h_{cc}^3}{6EI_w} - \frac{h_{cc}^3}{3EI_c} - \frac{h_{cc}}{GA_w}$$

Parametric framework for analysis:

- Select wall width (***L_w***) and wall ratio (***p***)
- Select number of stories ***N***. Calculate response factor and determine ***αH*** and period ***T***.
- For assumed wall ratio ***p*** calculate floor area per wall from ***$A_f = A_w/p$***.
- Story mass is then calculated from ***$m_s = A_f .(1\ t/m^2)$***.
- Response modification factor ***R=6*** for all cases except when minimum reinforcement requirements dictate smaller R.
- Calculate code ***V_t*** .
- Calculate wall moment and shear force.
- Normalized average axial wall load 0.015 of capacity.

Parametric framework for analysis: FE model



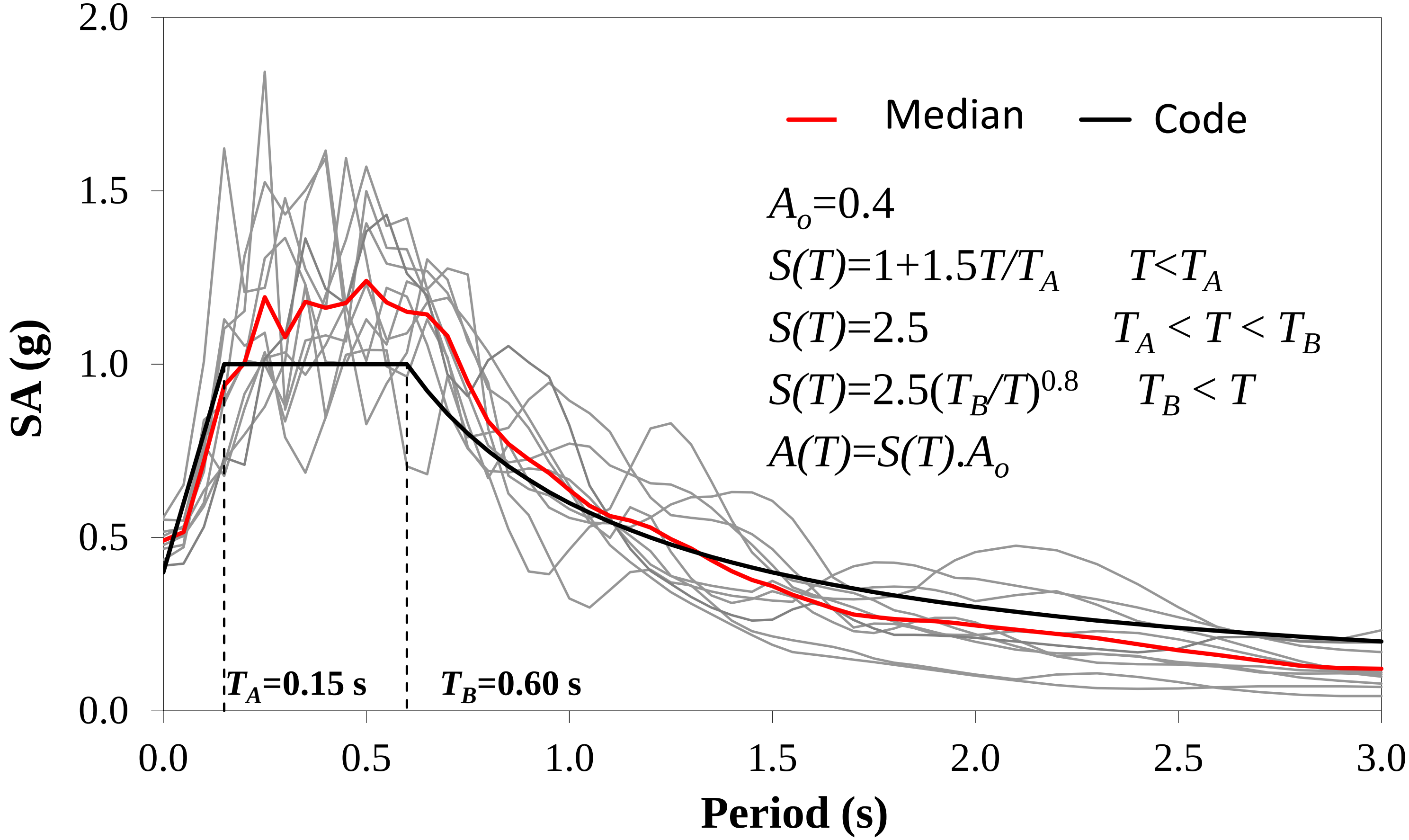
Parametric framework for analysis: ground motions

No	Event	Year	M_w	Station	R (km)	PGA (cm/s^2)	PGV (cm/s)	SF_{Spec}	D_{rms}
1	Imperial Valley	1979	6.5	Keystone Rd., El Centro Array #2	16.2	309	32.7	1.77	0.23
2	Kocaeli	1999	7.4	Duzce	17.1	308	50.7	1.52	0.17
3	Northridge	1994	6.7	Los Angeles, Brentwood V.A. Ho.	23.1	182	24.0	2.69	0.16
4	Northridge	1994	6.7	Pacoima-Kagel Canyon	10.6	424	50.9	1.20	0.09
5	Whittier Narrows	1987	6.1	7420 Jaboneria, Bell Gardens	16.4	216	28.0	1.98	0.26
6	Cape Mendocino	1992	7.1	89324 Rio Dell Overpass - FF	18.5	378	43.9	1.43	0.18
7	Northridge	1994	6.7	24389 LA - Century City CC North	25.7	218	25.2	2.11	0.27
8	Northridge	1994	6.7	24283 Moorpark - Fire Sta.	28	189	20.2	2.56	0.23
9	Loma Prieta	1989	6.9	Hollister Differential Array	25.8	274	35.6	1.47	0.29
10	Northridge	1994	6.7	LA - Fletcher Dr.	29.5	235	26.2	2.00	0.21

$$D_{rms} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\frac{SA_o(T_i)}{PGA_o} - \frac{SA_S(T_i)}{PGA_S}\right)^2}$$

$$SF_{Spect} = \frac{1}{3}\left(\frac{SA_S(T=0.1s)}{SA_o(T=0.1s)} + \frac{SA_S(T=0.4s)}{SA_o(T=0.4s)} + \frac{SA_S(T=0.85s)}{SA_o(T=0.85s)}\right)$$

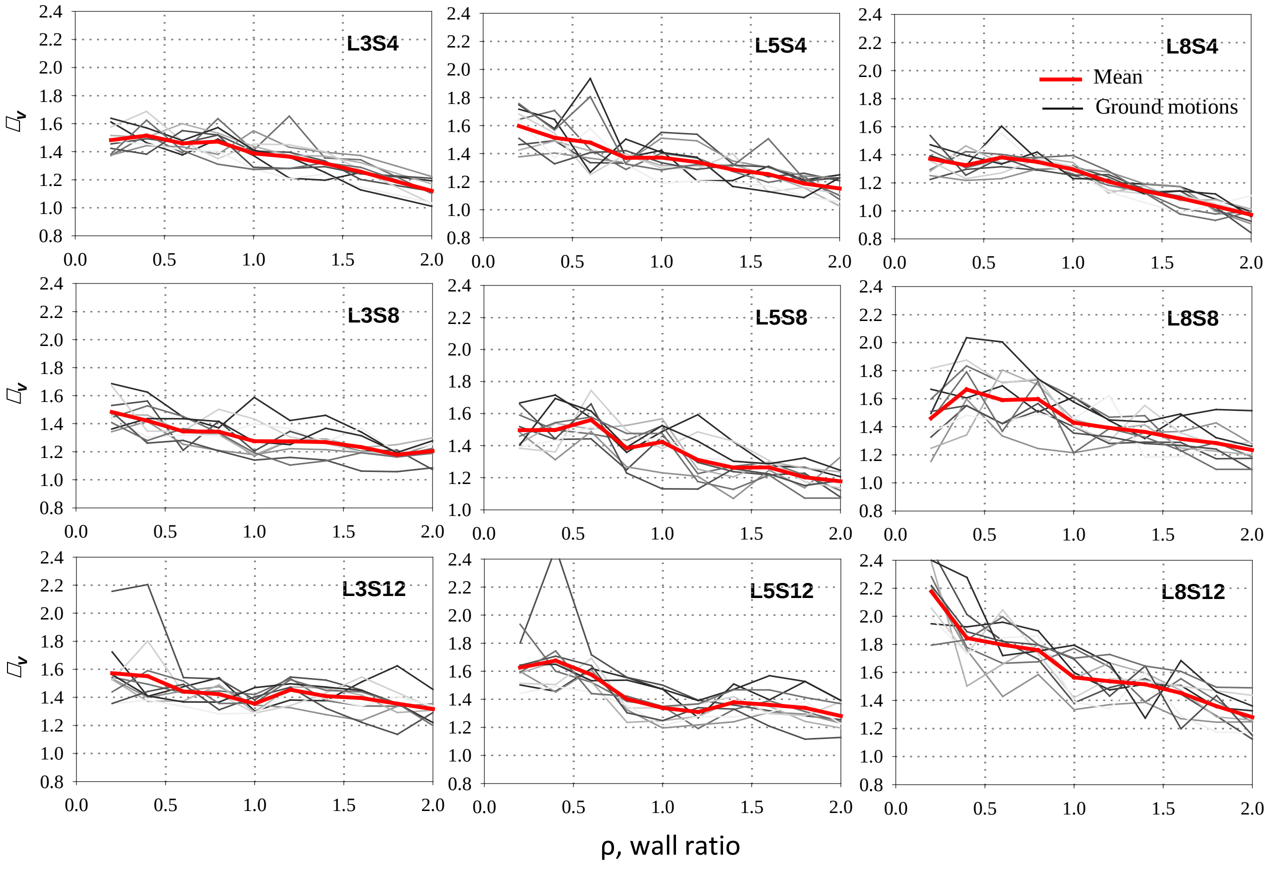
Parametric framework for analysis: ground motions

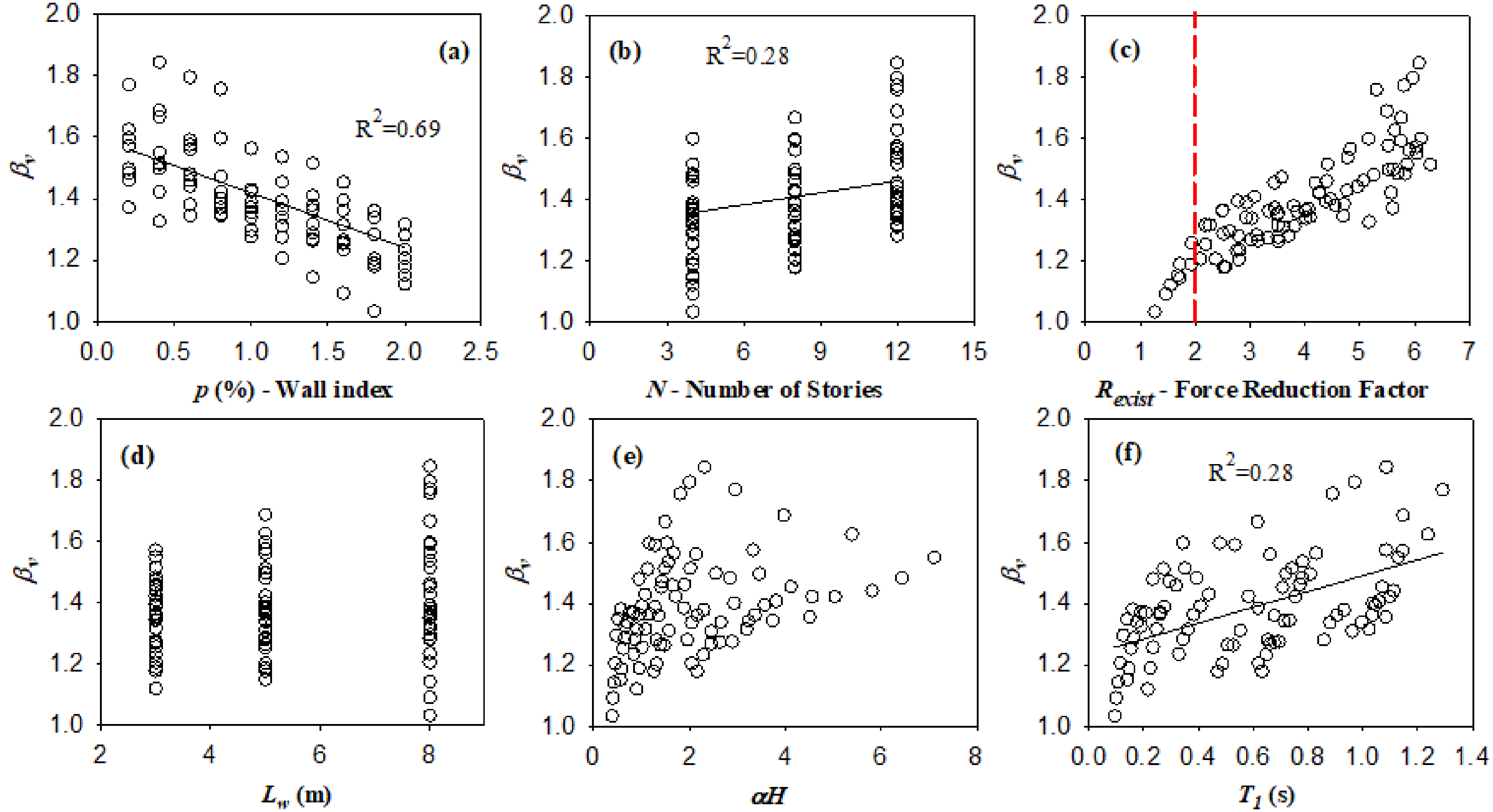


Dynamic shear force amplification factor:

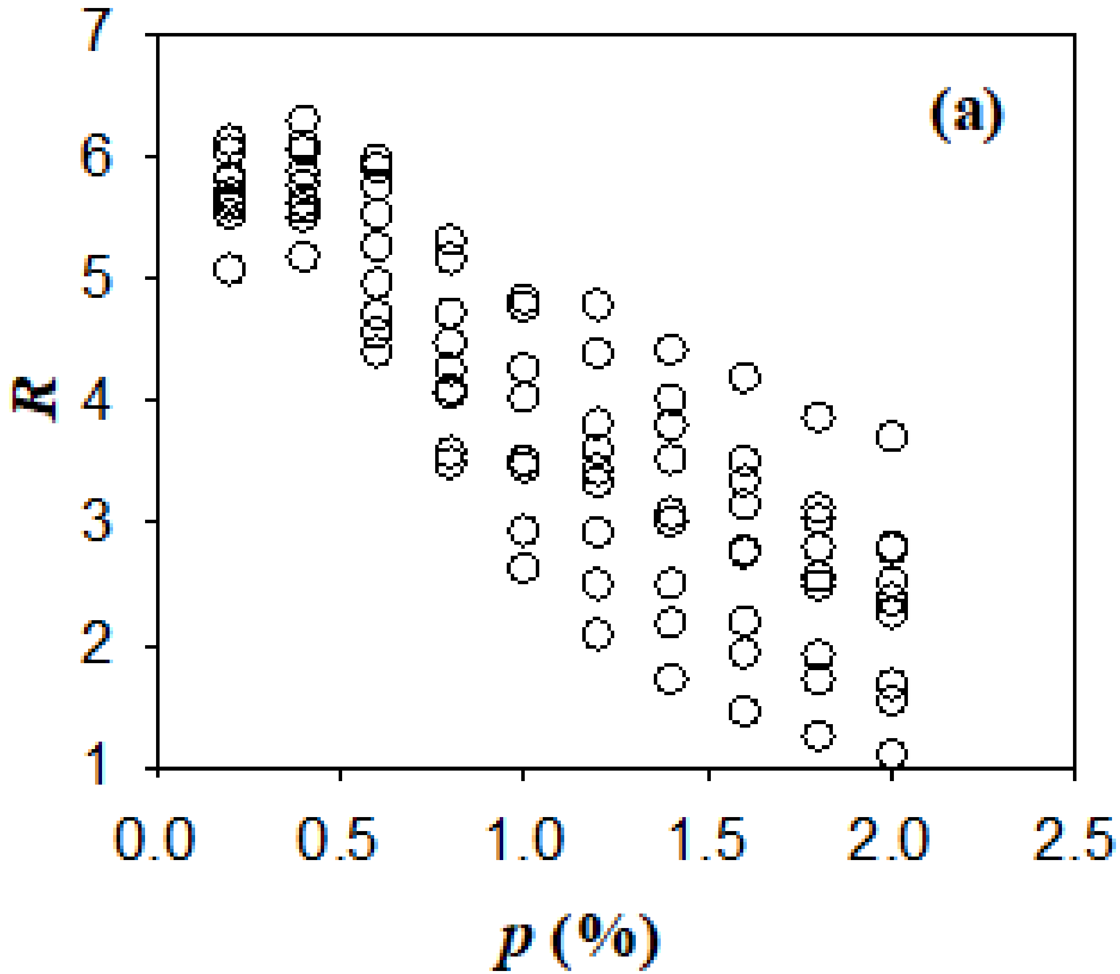
$$\beta_v = V_{dyn} / V_{st}$$

Static shear force V_{st} is calculated from a pushover analysis using the code specified equivalent force at the base. V_{dyn} is the maximum dynamic shear force at base.



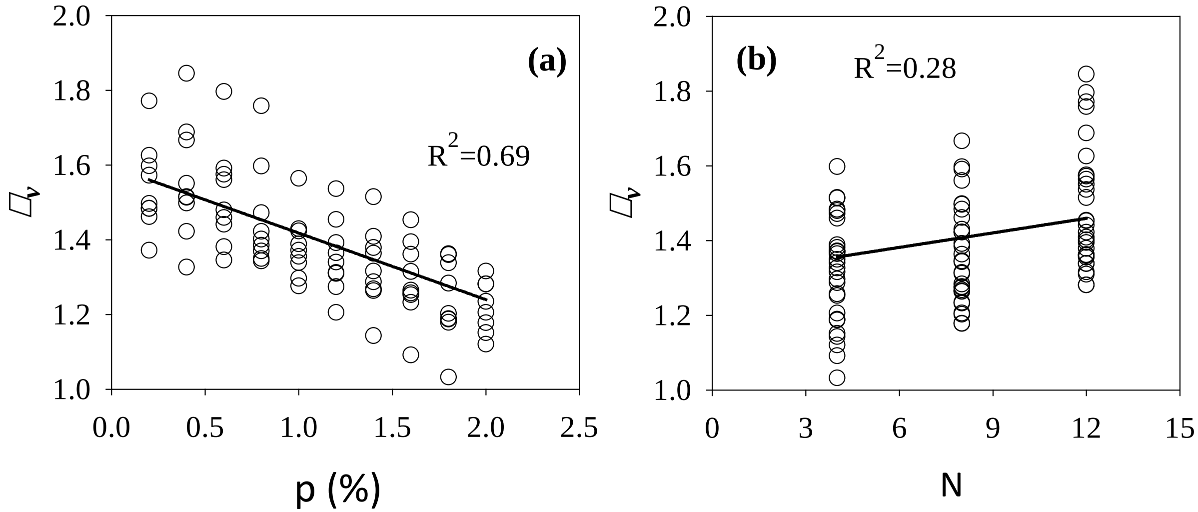


Variation of dynamic amplification factor with (a) wall index, (b) number of stories, (c) strength reduction factor, (d) wall length, (e) behavior factor and (f) first period.



Relation between the strength reduction factor and wall index

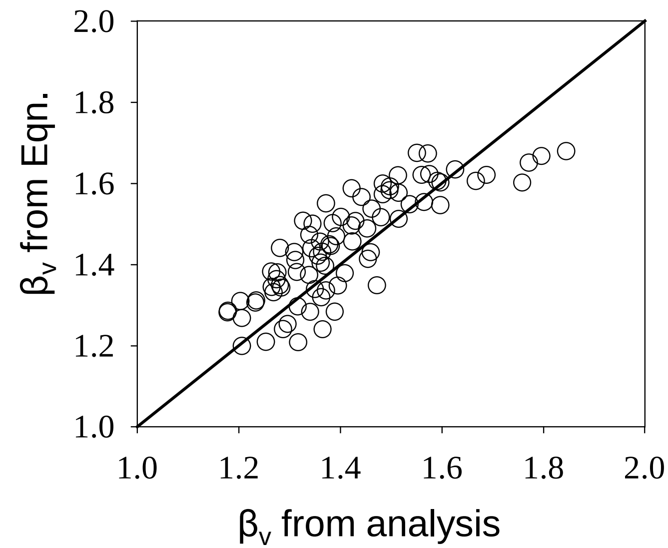
Dynamic wall shear force amplification factor β_v as it varies for ρ, N and R



$$\beta_v = 0.95 + 0.01N + 0.1R \qquad R > 2$$

$$\beta_v = 1 + (R-1)(0.15 + 0.01N) \qquad R \le 2$$

$$R_{exist} = \frac{M_d}{M_{yd}} R$$



In Sum

- The dominant effect that determines β_v is R, the measure of inelastic response.
- The number of stories, N, and period, determined jointly by ρ and stiffness, seem to have smaller influence.
- Keep in mind that the parametric study reported here is for buildings up to 12 stories and T = 1.5 s. Outside of these limits the predictive power of the equations may not be as strong.

And now, the real reason for my presence here:
a personal note.

October 14, 2011: my turn to say goodbye to all that.

Ladies and Gentlemen!

Though, to being a poet, I have no pretension,
May I request a moment of your attention?

A few words to honor Anil Chopra have I,
So now let me raise my glass, and straighten my tie!

In the jewel of the world, in Berkeley, we met,
And friends you make in Berkeley you never forget!

Anil and I are old friends, spanning four decades,
We have seen life’s sunrises and also its shades,

We have seen the earth shake and tall buildings sway,
And explained to students why structures act that way;

When I retired, Anil came on getting the news,
A chance to do the same I would not like to lose!

With regards for Anil and family, I close –
And I wish them all in future ‘une vie en rose’!!