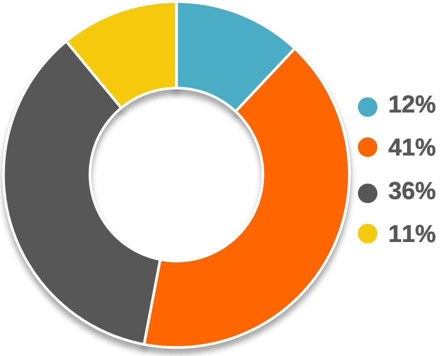
Elastic and Inelastic Building Torsion:
Revisited After 25 Years

Juan C. de la Llera, Oct. 2017

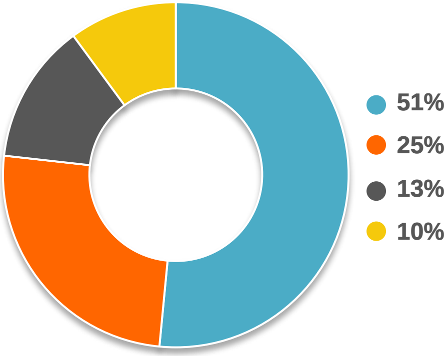
GLOBAL LOSSES

1980 – 2014

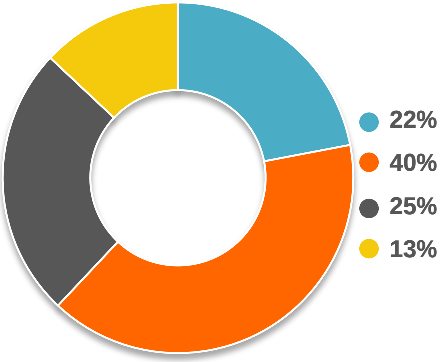
21.700 events



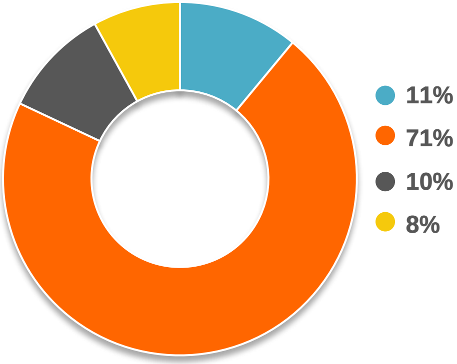
1.740.000 fatalities



Overall losses
US$ 4.200bn



Insured losses
US$ 1.100bn



● **Geophysical events**
(Earthquake, tsunami, volcanic activity)

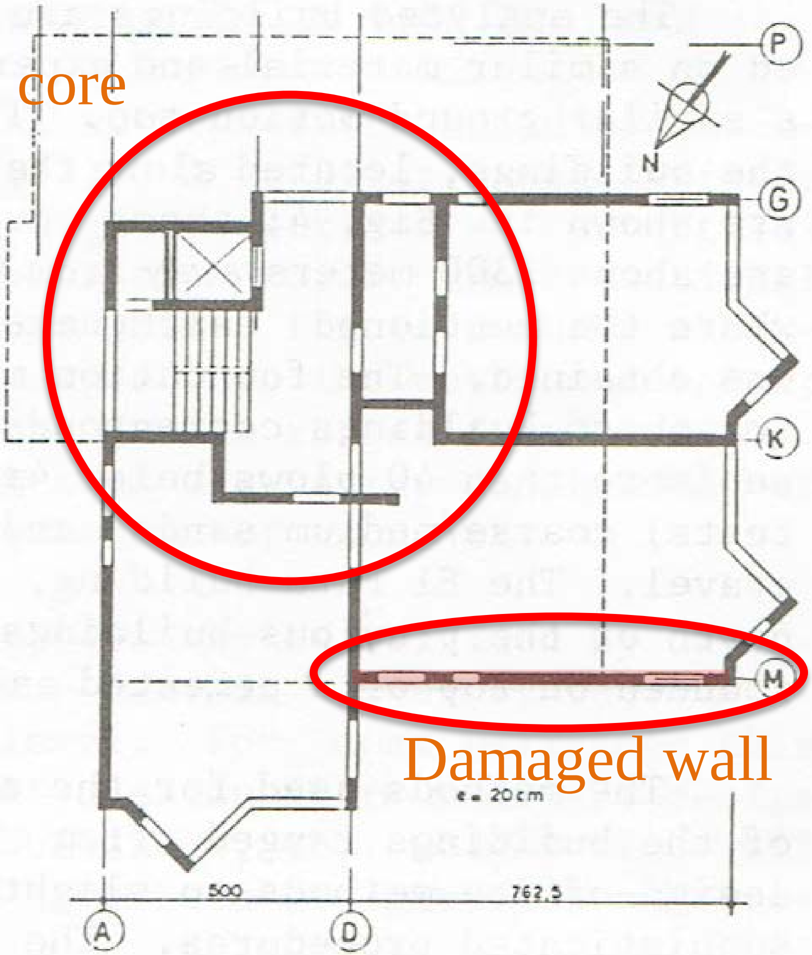
● **Hydrological events**
(Floods, mass movements)

● **Meteorological events**
(Tropical storm, extra tropical storm, convective storm, local storm)

● **Climatological events**
(Extreme temperature, drought, forest fire)

Munich RE, NatCatSERVICE

Torsional response: Chile (1985)



Strong core

Damaged wall

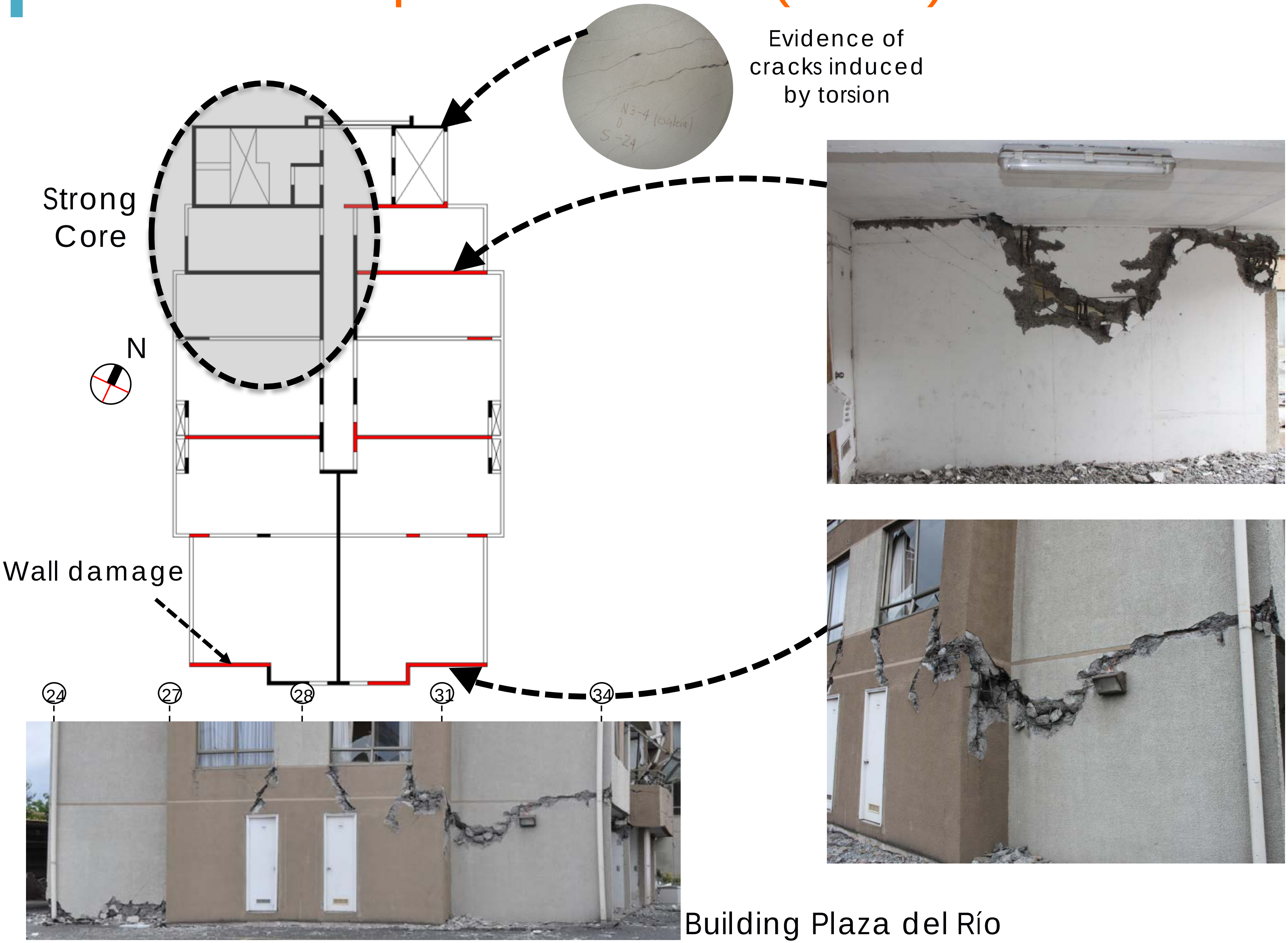
Fig. 6 El Faro Building Plan

Torsional response: Mexico (1985), Japan (1995)

Corner buildings, Mexico City

Mitsubishi Bank building, Kobe

Torsional response: Chile (2010)

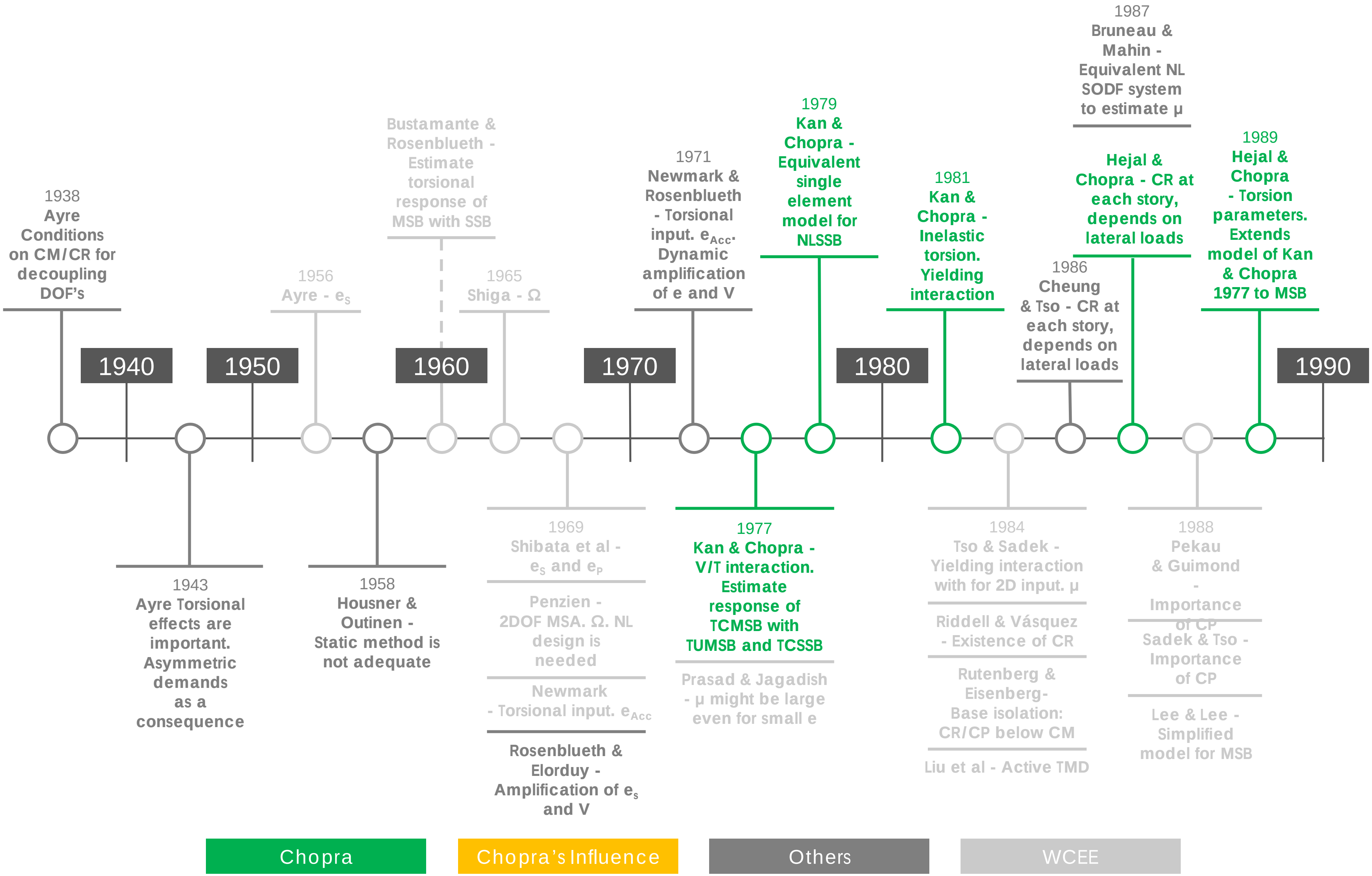


Evidence of cracks induced by torsion

Building Plaza del Río

Torsional response: Mexico (2017)

Timeline: Phase I



1938
Ayre Conditions on CM/CR for decoupling DOF’s

1943
Ayre Torsional effects are important. Asymmetric demands as a consequence

1956
Ayre - e_S

1958
Housner & Outinen - Static method is not adequate

Bustamante & Rosenblueth - Estimate torsional response of MSB with SSB

1965
Shiga - Ω

1969
Shibata et al - e_S and e_P

Penzien - 2DOF MSA. Ω. NL design is needed

Newmark - Torsional input. e_{Acc}

Rosenblueth & Elorduy - Amplification of e_s and V

1971
Newmark & Rosenblueth - Torsional input. e_{Acc}. Dynamic amplification of e and V

1977
Kan & Chopra - V/T interaction. Estimate response of TCMSB with TUMSB and TCSSB

Prasad & Jagadish - μ might be large even for small e

1979
Kan & Chopra - Equivalent single element model for NLSSB

1981
Kan & Chopra - Inelastic torsion. Yielding interaction

1984
Tso & Sadek - Yielding interaction with for 2D input. μ

Riddell & Vásquez - Existence of CR

Rutenberg & Eisenberg- Base isolation: CR/CP below CM

Liu et al - Active TMD

1986
Cheung & Tso - CR at each story, depends on lateral loads

1987
Bruneau & Mahin - Equivalent NL SODF system to estimate μ

Hejal & Chopra - CR at each story, depends on lateral loads

1988
Pekau & Guimond - Importance of CP

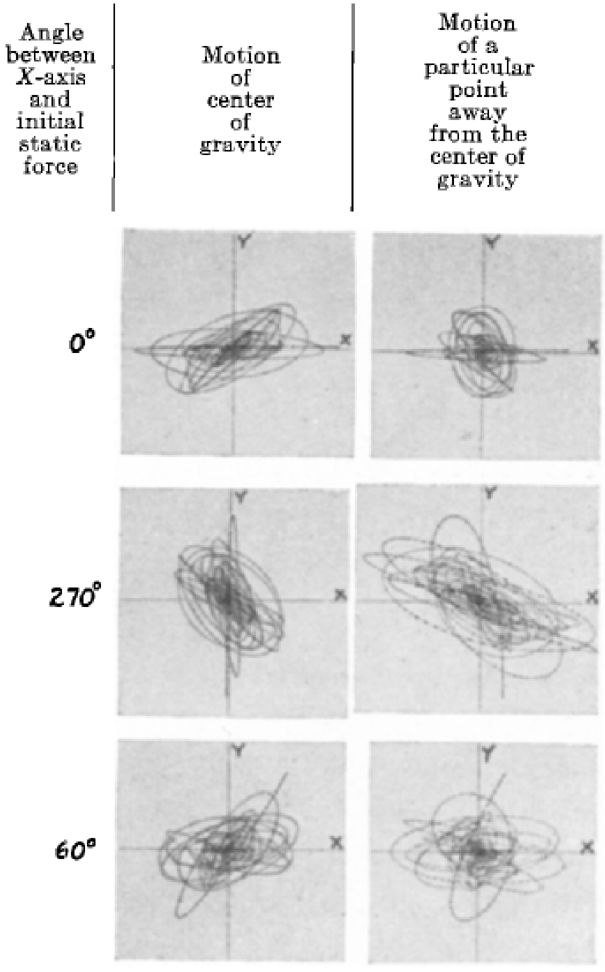
Sadek & Tso - Importance of CP

Lee & Lee - Simplified model for MSB

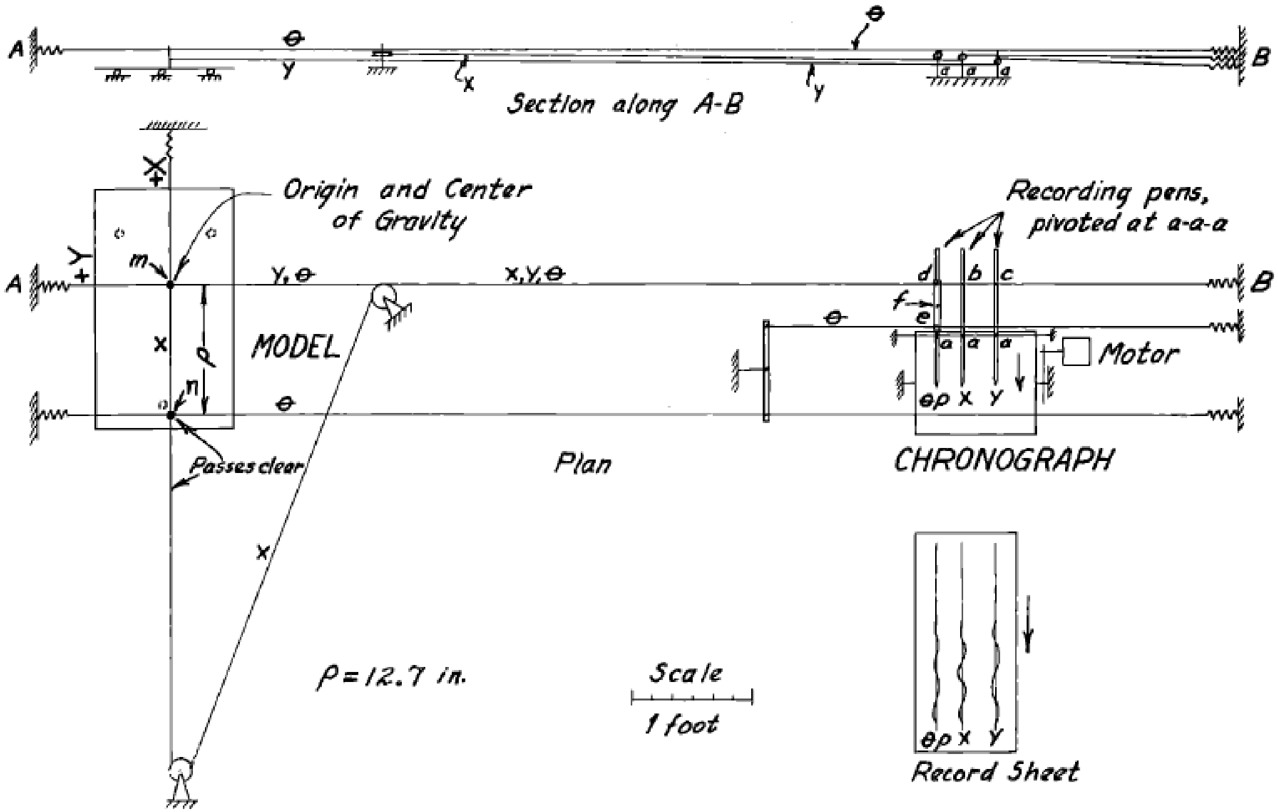
1989
Hejal & Chopra - Torsion parameters. Extends model of Kan & Chopra 1977 to MSB

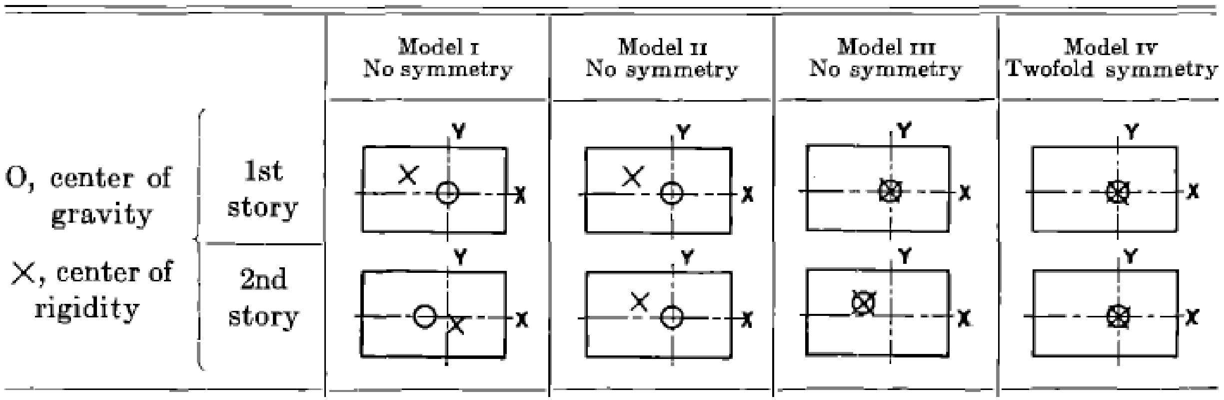
🟩 Chopra
🟨 Chopra’s Influence
⬛ Others
⬜ WCEE

Ayre, 1938



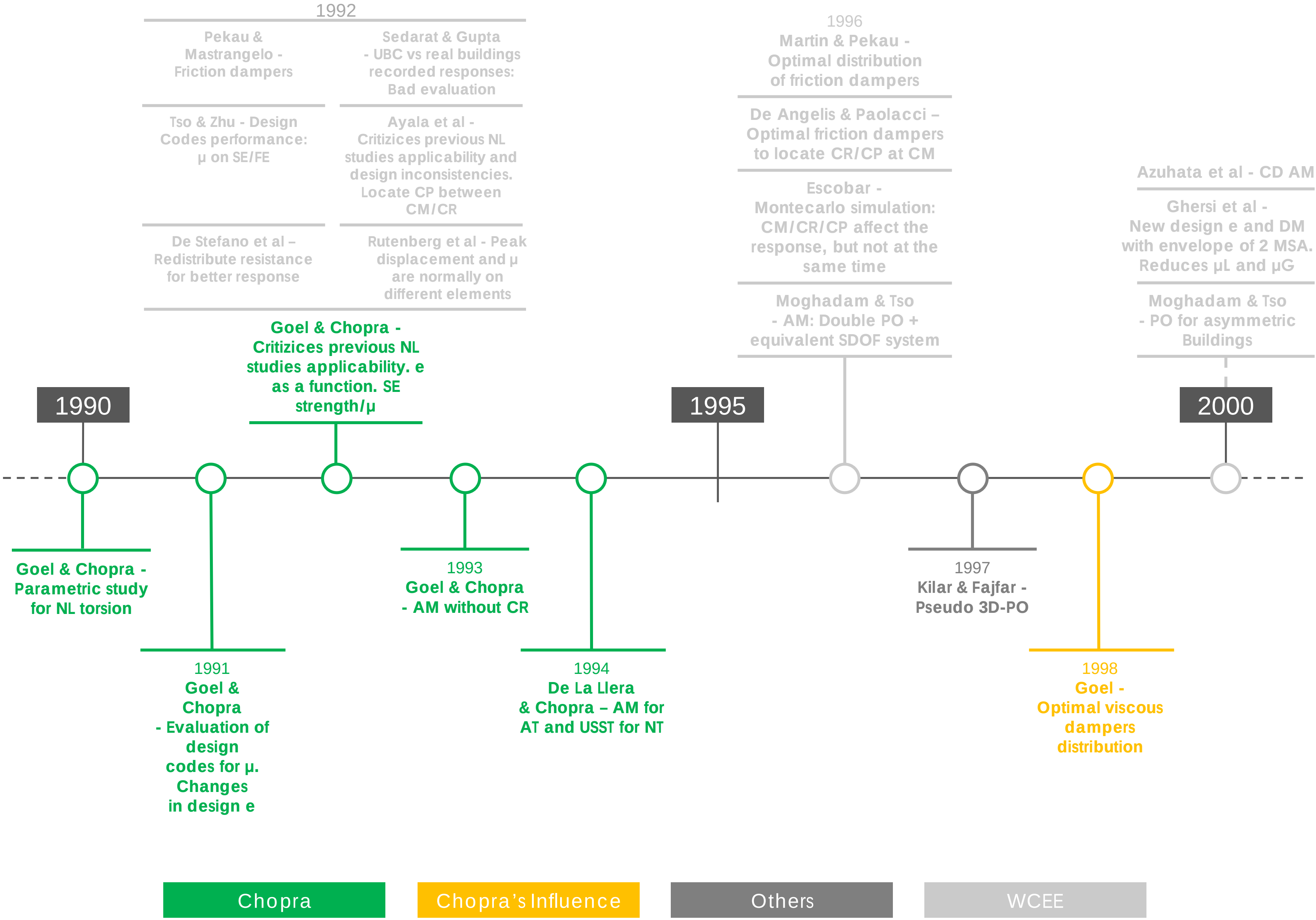
No symmetry





		Model I No symmetry	Model II No symmetry	Model III No symmetry	Model IV Twofold symmetry
O, center of gravity X, center of rigidity	1st story				
	2nd story				

Timeline: Phase II



1990

Goel & Chopra - Parametric study for NL torsion

1991
Goel & Chopra - Evaluation of design codes for μ. Changes in design e

1992

Pekau & Mastrangelo - Friction dampers

Sedarat & Gupta - UBC vs real buildings recorded responses: Bad evaluation

Tso & Zhu - Design Codes performance: μ on SE/FE

Ayala et al - Critizices previous NL studies applicability and design inconsistencies. Locate CP between CM/CR

De Stefano et al – Redistribute resistance for better response

Rutenberg et al - Peak displacement and μ are normally on different elements

Goel & Chopra - Critizices previous NL studies applicability. e as a function. SE strength/μ

1993
Goel & Chopra - AM without CR

1994
De La Llera & Chopra – AM for AT and USST for NT

1995

1996
Martin & Pekau - Optimal distribution of friction dampers

De Angelis & Paolacci – Optimal friction dampers to locate CR/CP at CM

Escobar - Montecarlo simulation: CM/CR/CP affect the response, but not at the same time

Moghadam & Tso - AM: Double PO + equivalent SDOF system

1997
Kilar & Fajfar - Pseudo 3D-PO

1998
Goel - Optimal viscous dampers distribution

2000

Azuhata et al - CD AM

Ghersi et al - New design e and DM with envelope of 2 MSA. Reduces μL and μG

Moghadam & Tso - PO for asymmetric Buildings

🟩 Chopra

🟨 Chopra's Influence

⬛ Others

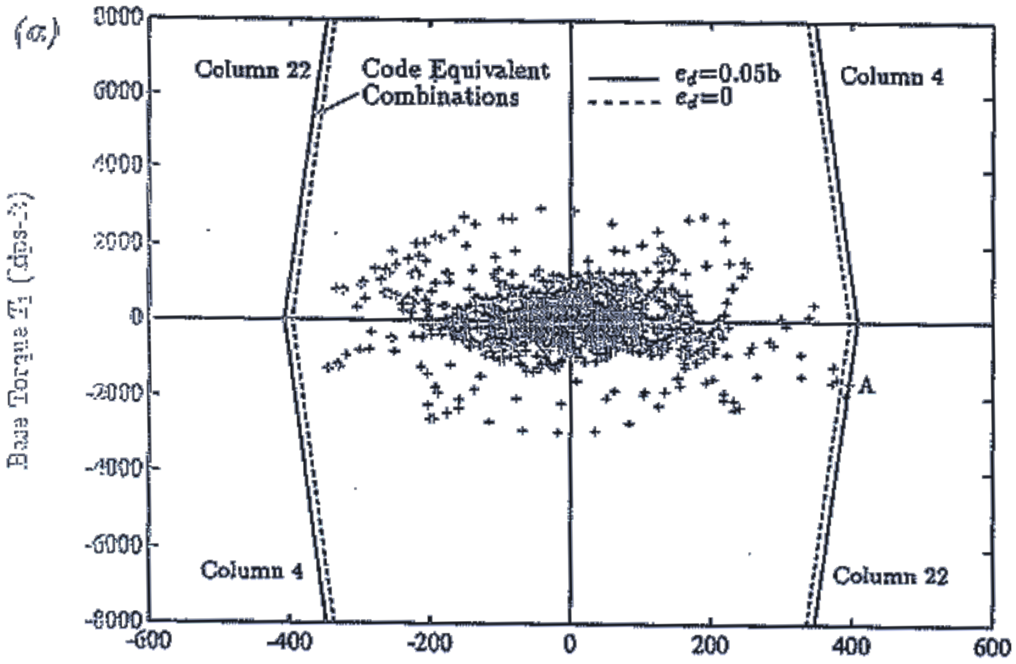
⬜ WCEE

Accidental Torsion

Seminar AKC

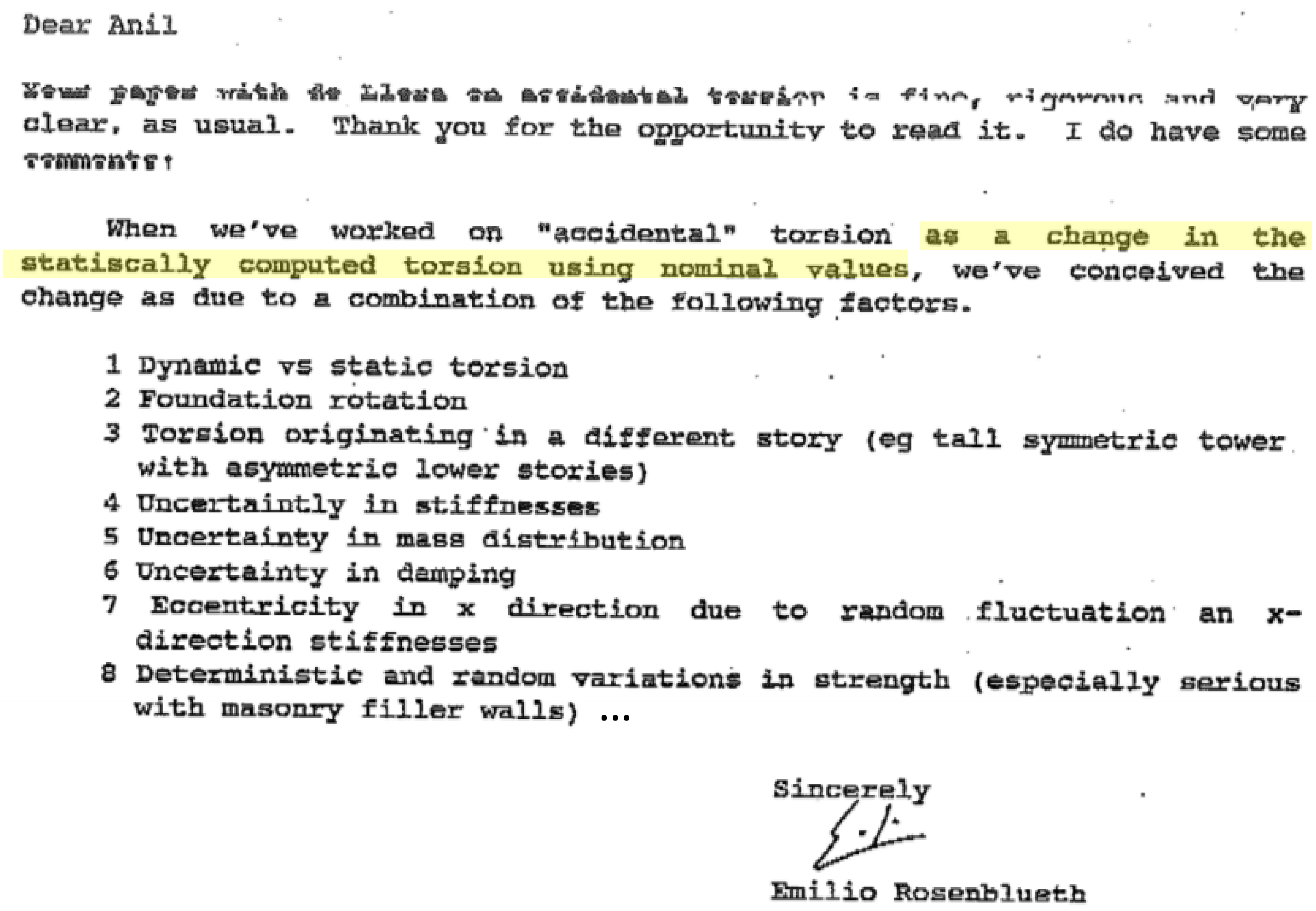
Accidental torsion

Accidental torsion is a term used to represent lateral-torsional coupling due to factors that are not, or cannot, be accounted for by current modeling and analysis procedures. It includes random and epistemic uncertainties, and in principle, will be present regardless of our modeling and measuring attempts. Uncertainty quantification techniques nowadays try to extract the epistemic component of accidental torsion to leave it as a random component. **It is a demand problem and includes uncertainties in the input and parameters of the system**



Example of torsion in a nominally symmetric structure

Important letters...



Dear Anil

Your paper with de Llera on accidental torsion is fine, rigorous and very clear, as usual. Thank you for the opportunity to read it. I do have some comments:

When we've worked on "accidental" torsion as a change in the statiscally computed torsion using nominal values, we've conceived the change as due to a combination of the following factors.

1 Dynamic vs static torsion
2 Foundation rotation
3 Torsion originating in a different story (eg tall symmetric tower with asymmetric lower stories)
4 Uncertaintly in stiffnesses
5 Uncertainty in mass distribution
6 Uncertainty in damping
7 Eccentricity in x direction due to random fluctuation an x-direction stiffnesses
8 Deterministic and random variations in strength (especially serious with masonry filler walls) ...

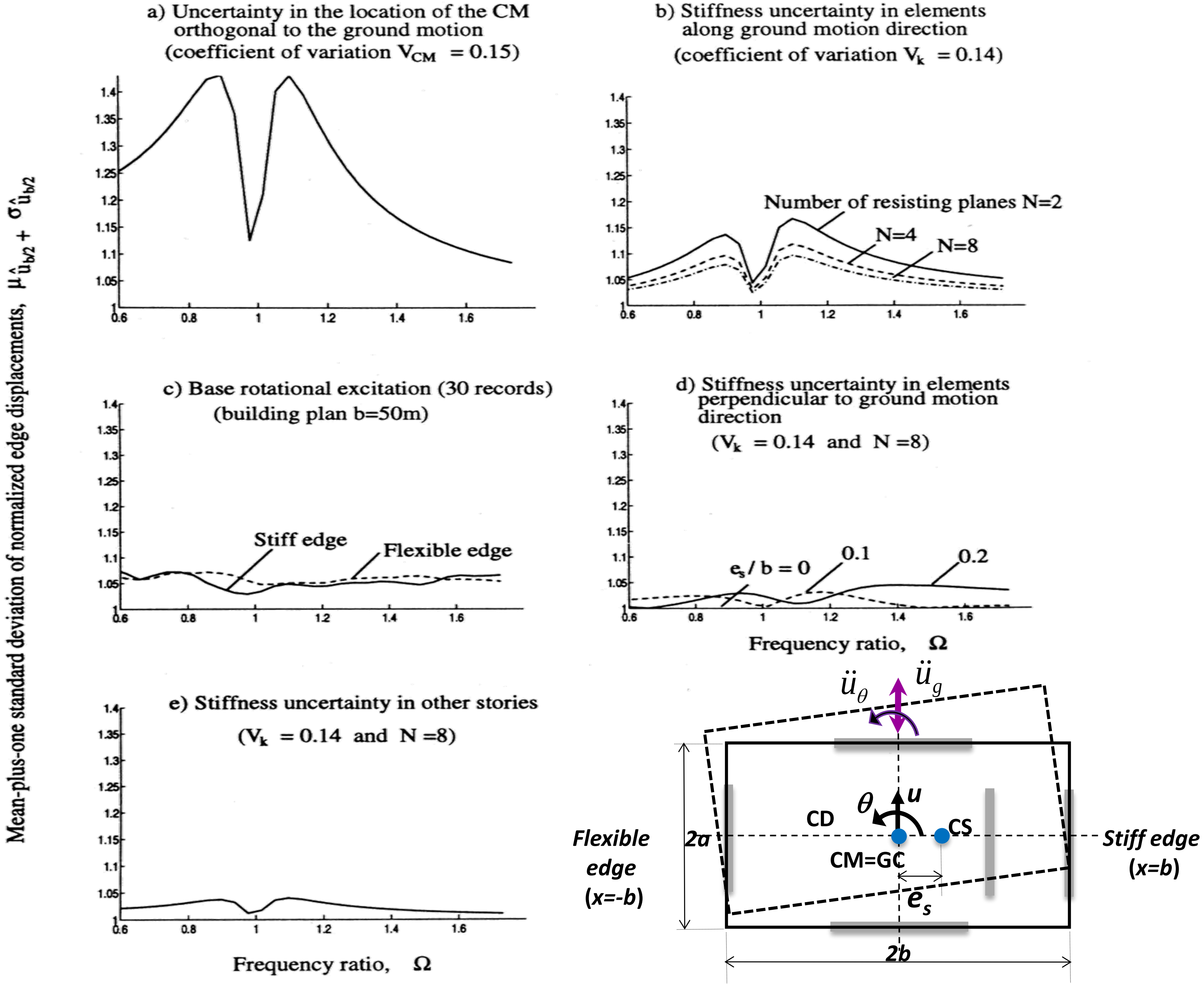
Sincerely

Emilio Rosenblueth

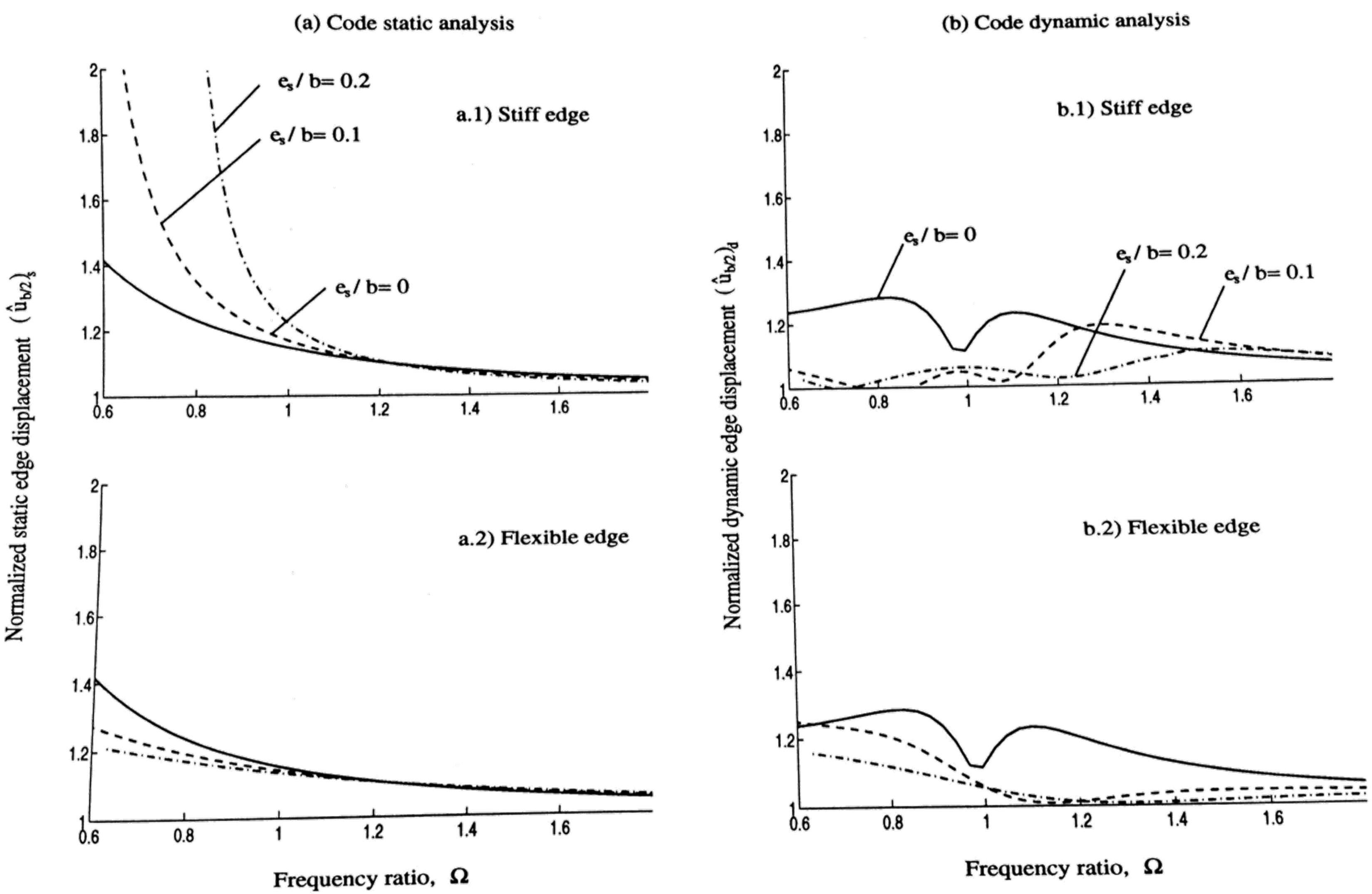
Research questions

- How significant is the effect of accidental torsion in building design? Could it be neglected?
- What is the relative importance on the building response of the different sources of accidental torsion?
- How does the code-static and dynamic response amplifications due to accidental torsion compare with each other?
- Is it possible to account for accidental torsion in building design in a simpler way rather than moving the CM in $\pm\beta b$?

Sources of accidental torsion



Static vs. dynamic models ($e_a = \pm\beta b$)

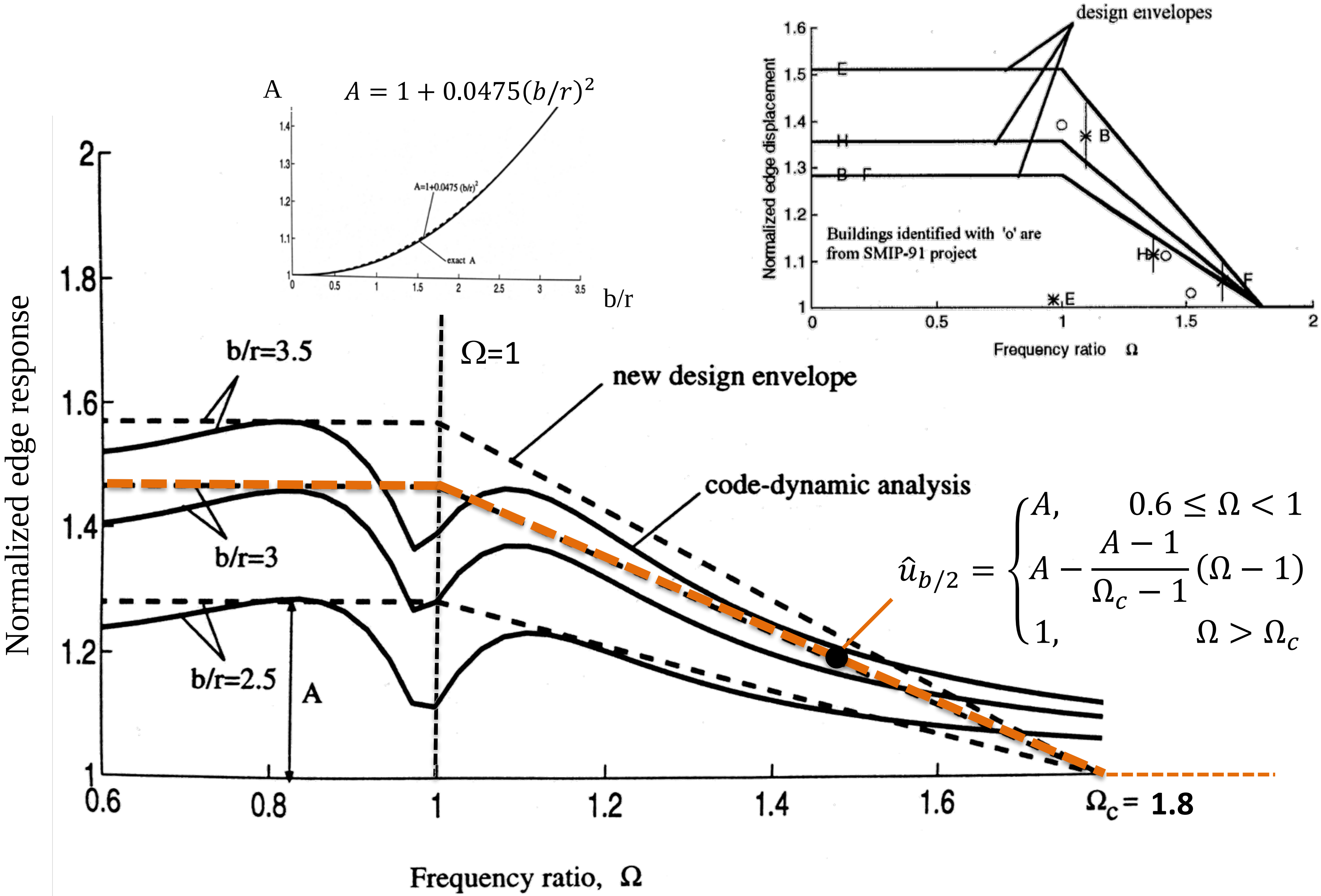


(a) Code static analysis

(b) Code dynamic analysis

Figure 3: Normalized edge displacement $\hat{u}_{b/2}$ computed from code-static and dynamic analyses for accidental torsion in systems with $T_y = 1$ sec, square plan $b/r = \sqrt{6}$, and static eccentricity $e_s/b = 0, 0.1,$ and 0.2

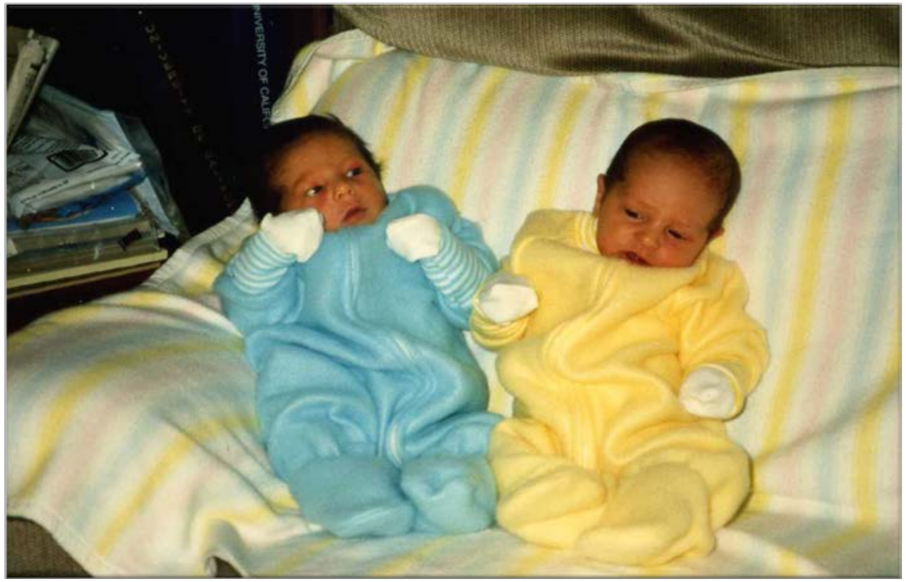
Proposed increase in edge deformations



$$A = 1 + 0.0475(b/r)^2$$

$$\hat{u}_{b/2} = \begin{cases} A, & 0.6 \leq \Omega < 1 \\ A - \dfrac{A-1}{\Omega_c - 1}(\Omega - 1) \\ 1, & \Omega > \Omega_c \end{cases}$$

While school progressed...

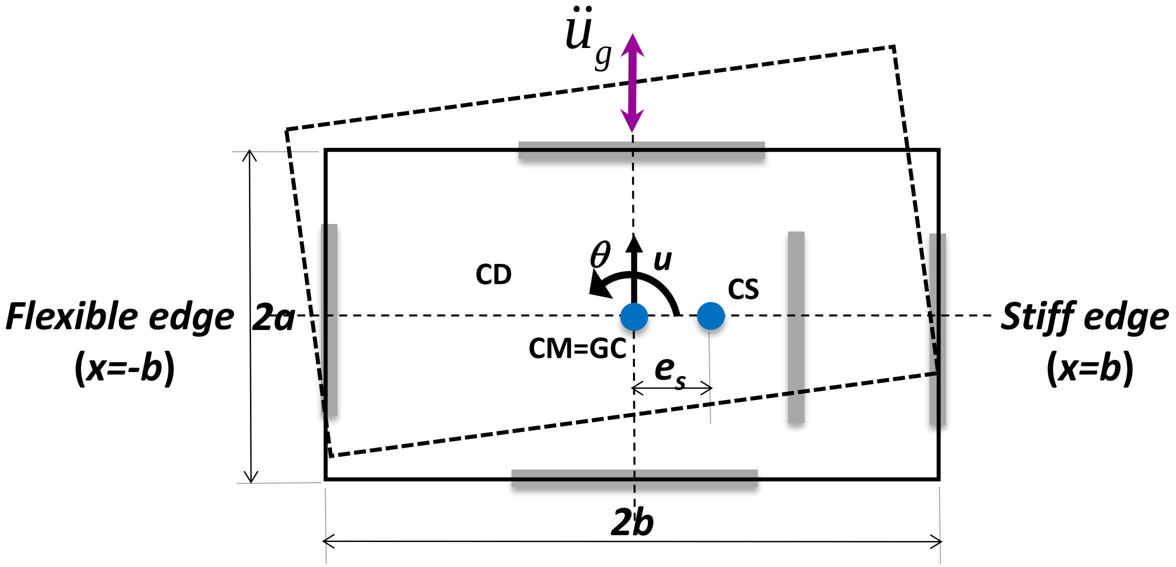


Natural Torsion

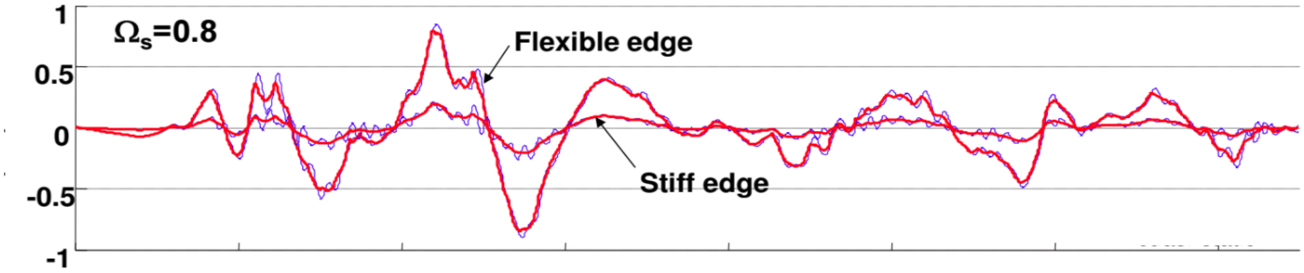
Seminar AKC

Natural torsion

Lateral-torsional coupling of a building implies translational and rotational motions of the floor diaphragms, thus inducing uneven inelastic deformation demands on structural elements of different resisting planes across the building plan. Such uneven demands may be controlled by conventional or innovative means. **In any case, the phenomenon can be interpreted as a seismic demand problem**.



T_s=0.3s, ξ_s=0.05, e_s=0.25ρ, T_b=2.5s, ξ_b=0.20

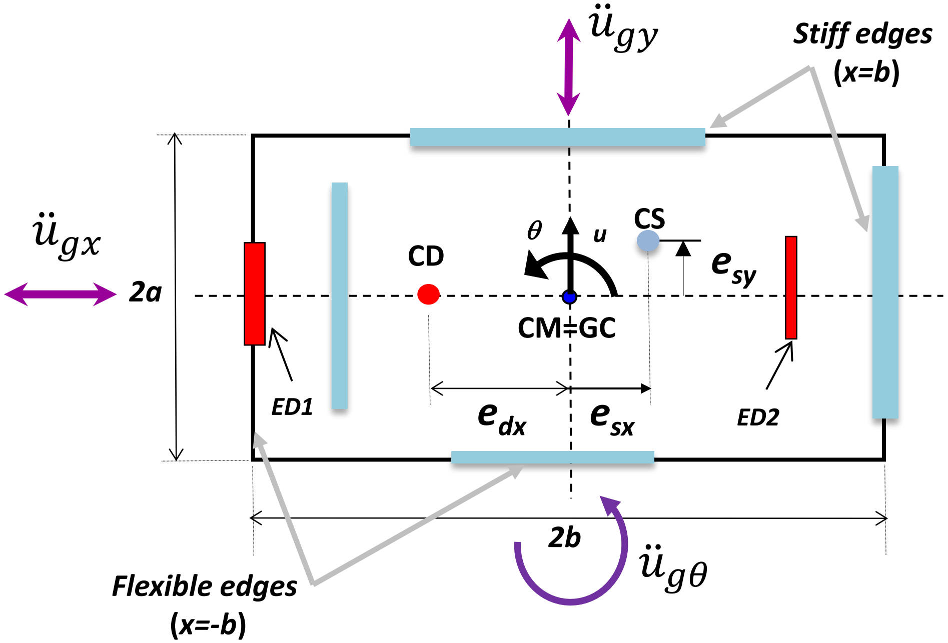


Equations of motion

$$\begin{pmatrix}\ddot{u}_x\\ \ddot{u}_y\\ \rho\ddot{u}_\theta\end{pmatrix} + M^{-1}C\begin{pmatrix}\dot{u}_x\\ \dot{u}_y\\ \rho\dot{u}_\theta\end{pmatrix} + \underbrace{\omega_\theta^2\begin{bmatrix}\frac{1}{\Omega_x^2} & 0 & -\frac{e_{sy}}{\Omega_x^2\rho}\\ 0 & \frac{1}{\Omega_y^2} & \frac{e_{sx}}{\Omega_y^2\rho}\\ -\frac{e_{sy}}{\Omega_x^2\rho} & \frac{e_{sx}}{\Omega_y^2\rho} & 1\end{bmatrix}\begin{pmatrix}u_x\\ u_y\\ \rho u_\theta\end{pmatrix}}_{M^{-1}L_r^T f_r} + M^{-1}\overset{\text{Torsional control term}}{\boxed{L_d^T f_d}} = -\begin{pmatrix}\ddot{u}_{gx}\\ \ddot{u}_{gy}\\ \rho\ddot{u}_{g\theta}\end{pmatrix}$$

Critical parameters:

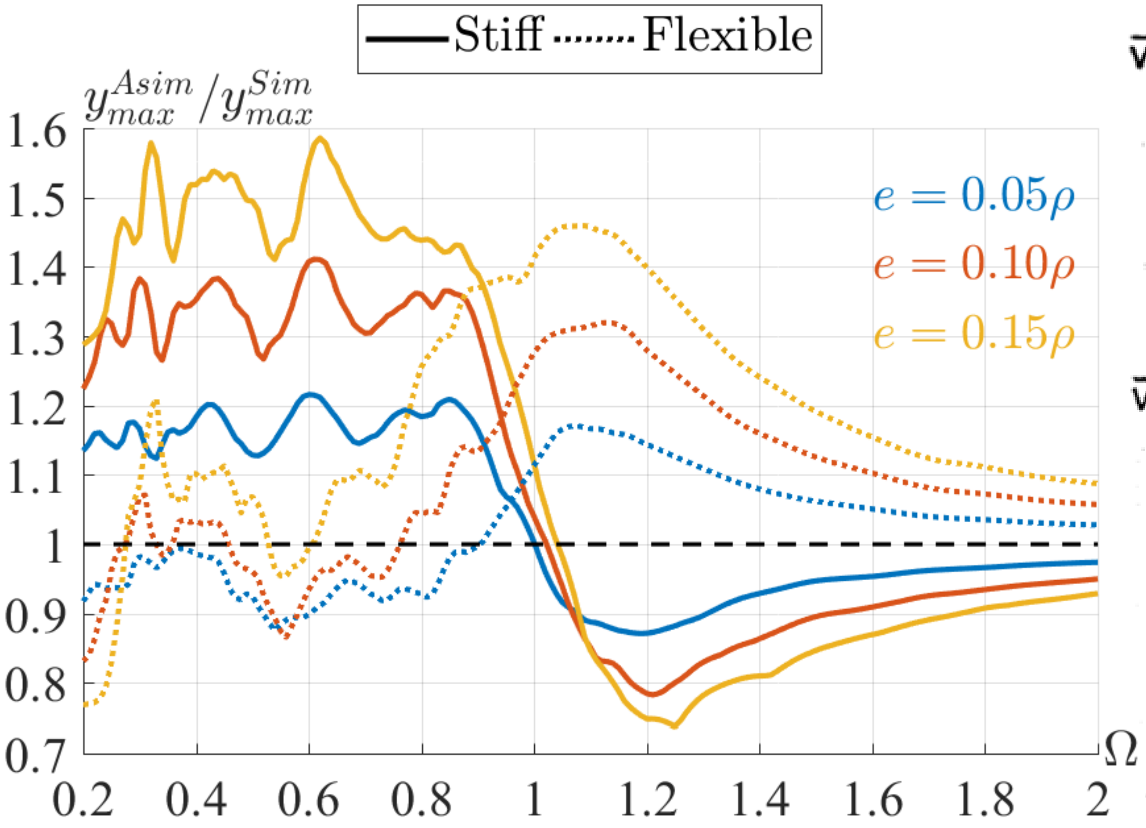
$$\Omega, \omega_y, \xi, \frac{e_s}{\rho}, \omega_d, \xi_d, \frac{e_d}{\rho}, \frac{b}{\rho}, \dots$$



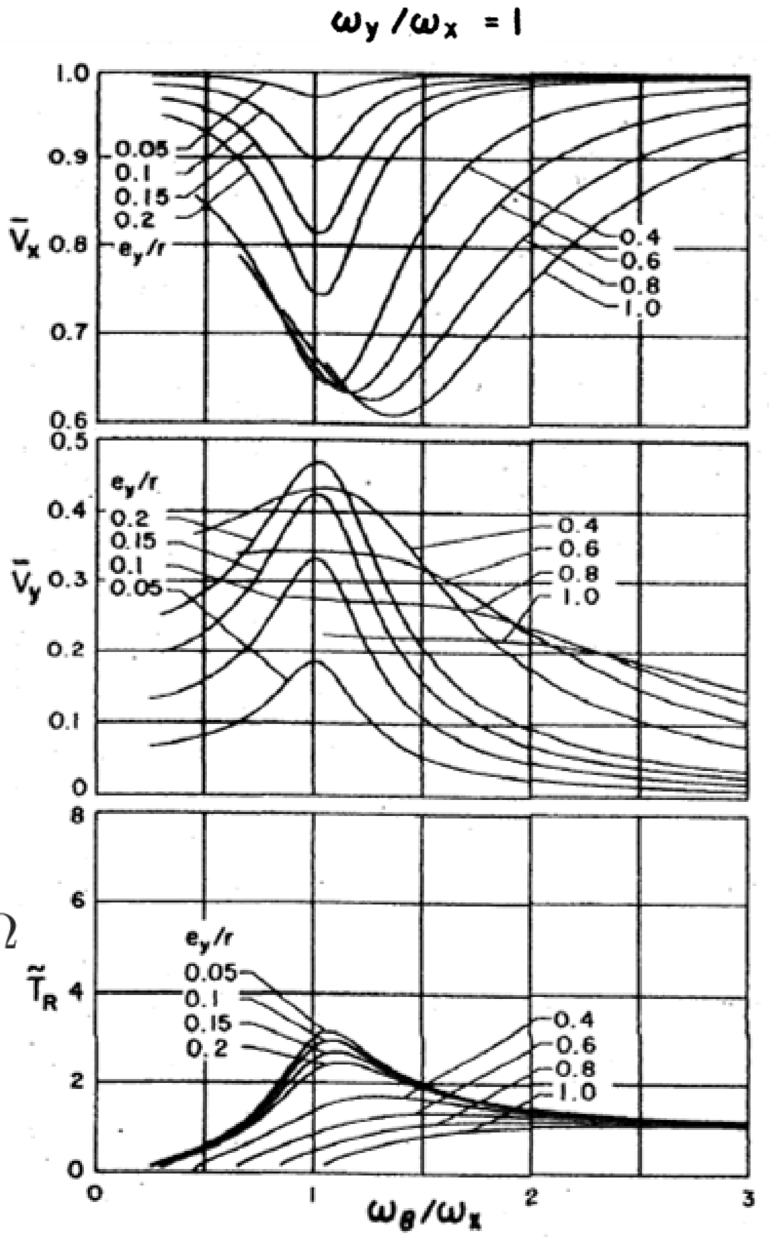
Research questions

- What are the elastic/inelastic dynamic amplifications in the element displacements and forces due to lateral-torsional coupling?-- static versus dynamic eccentricities.
- Is it possible to uncouple the translational and rotational motions?---Centers of rigidity, stiffness, shear, twist,...
- Are the models used comparable? Is there a conceptual framework available to interpret these different results?
- Would it be possible to control the lateral-torsional response of a structure by other means rather than changing its design, i.e. the distribution of stiffness and strength?

1. Torsional amplification



Average of 6 records (b/a=2, T_y=1s, Chile, 2010)



Kan & Chopra, 1977

2. Static vs dynamic eccentricity ($e_d = \alpha e_s$)

The natural **eccentricity** is modified by a **dynamic amplification factor**

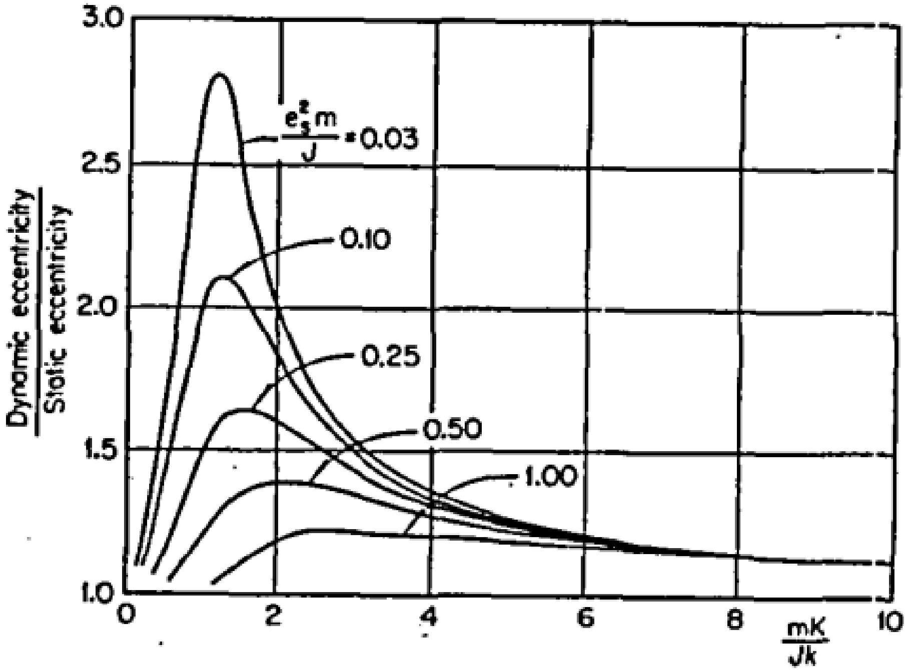
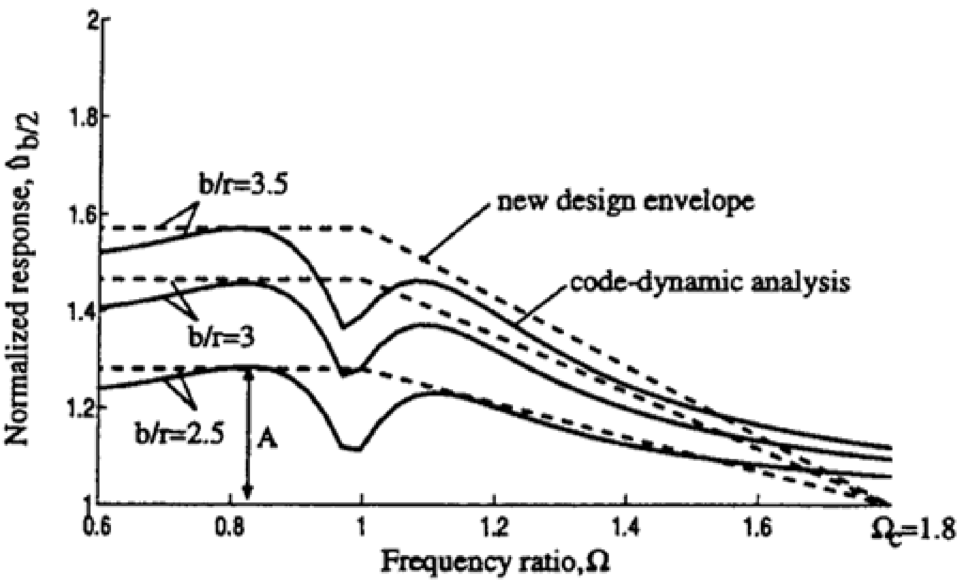


Fig.10 Magnification factor for eccentricity

Rosenblueth & Elorduy, 1969



de la Llera & Chopra, 2001

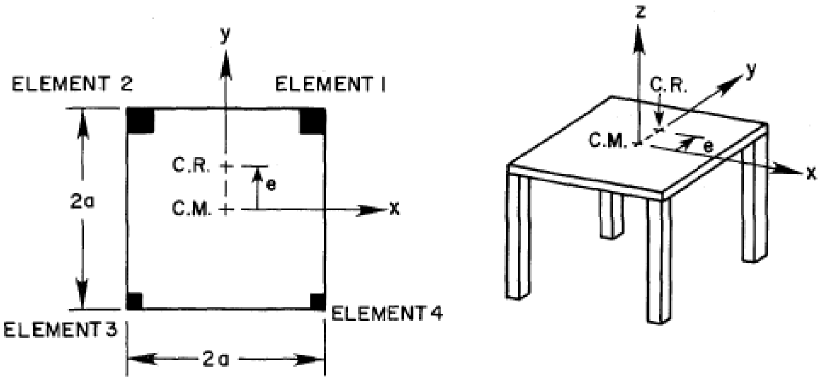
3. Inelastic vs. elastic behavior

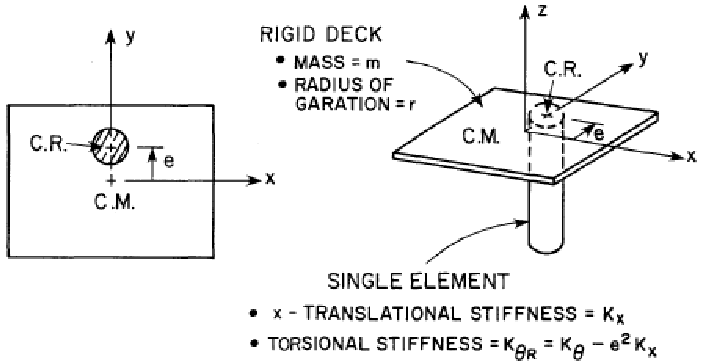
Necessity of inelastic analyses

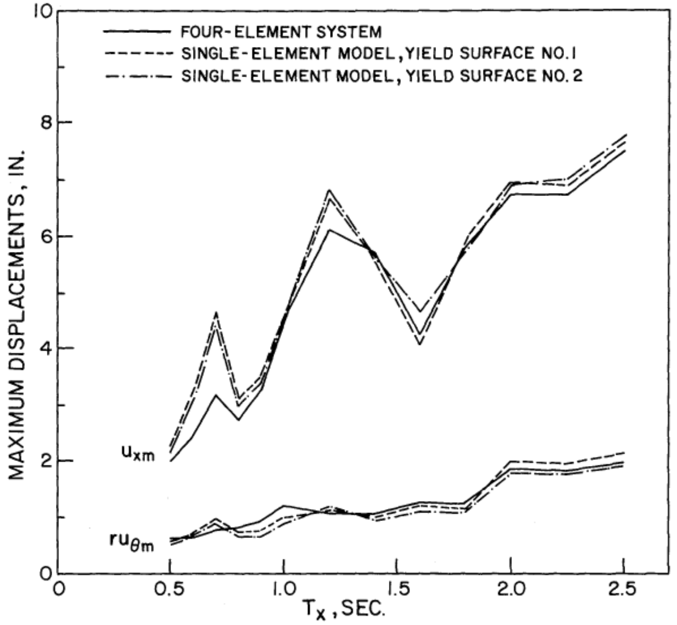
1. Better understanding of the problem
2. Consistency with ductile design

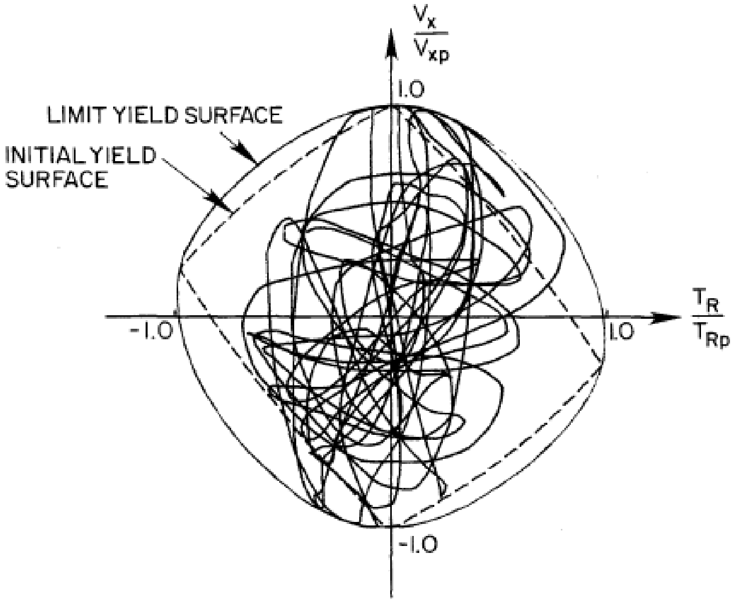
Development of simplified models

Accurate, economic and practical.









Kan & Chopra, 1979

4. Inelastic behavior

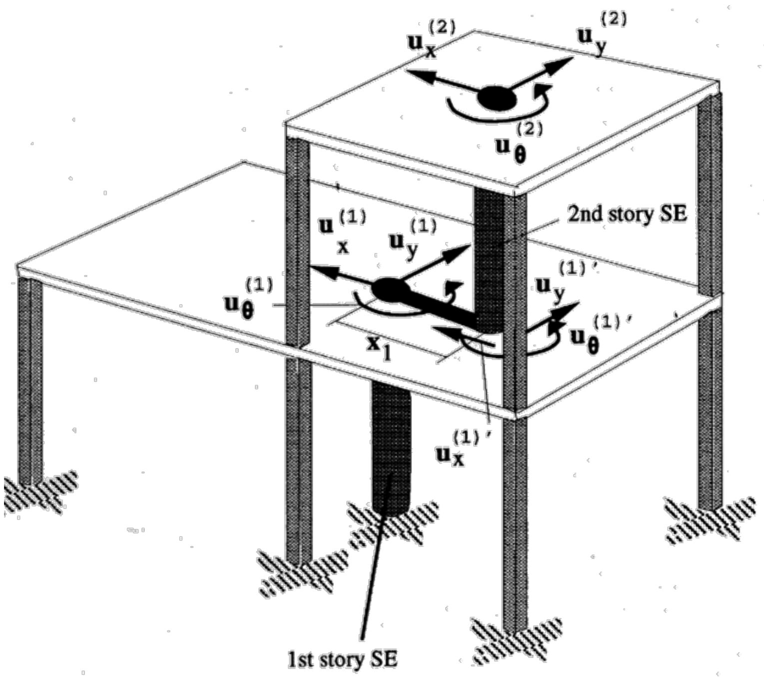
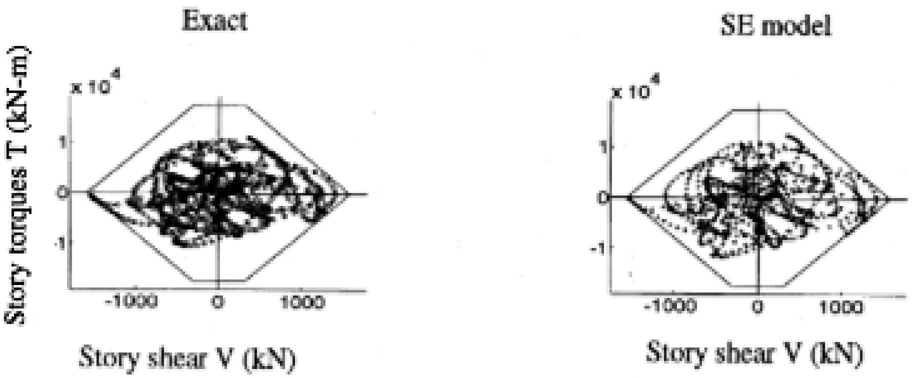
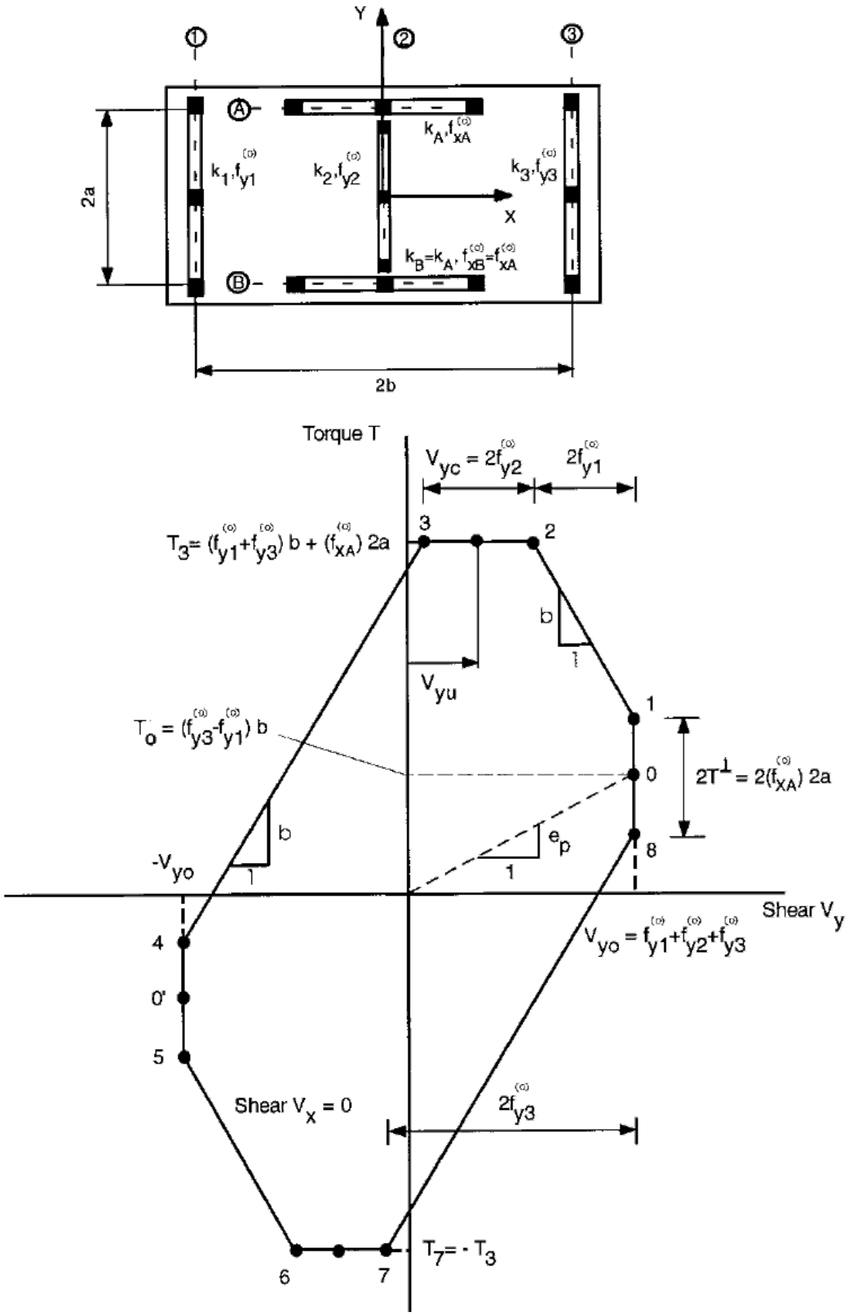


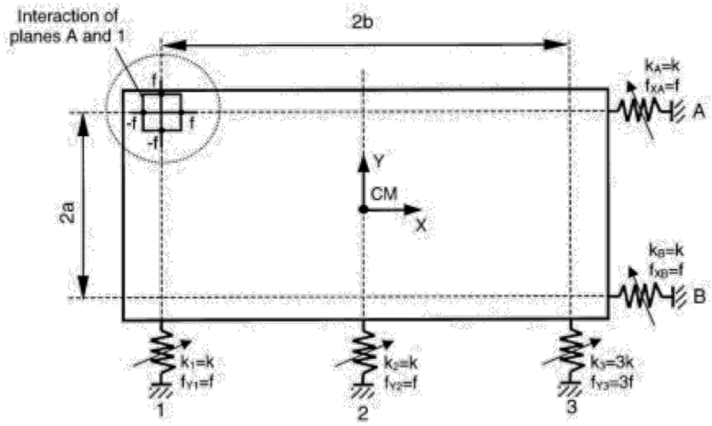
Figure 2. SE model for a building with non-aligned centres of mass



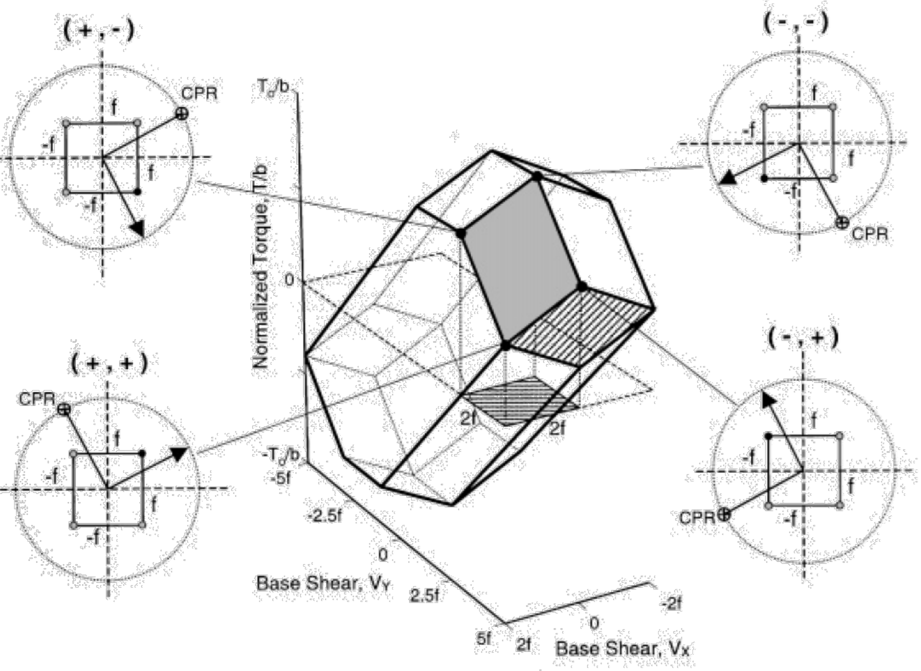


De La Llera & Chopra, 1995
SEM and yield surface for multistory buildings

4. Inelastic behavior



a) Mechanical model of the building example



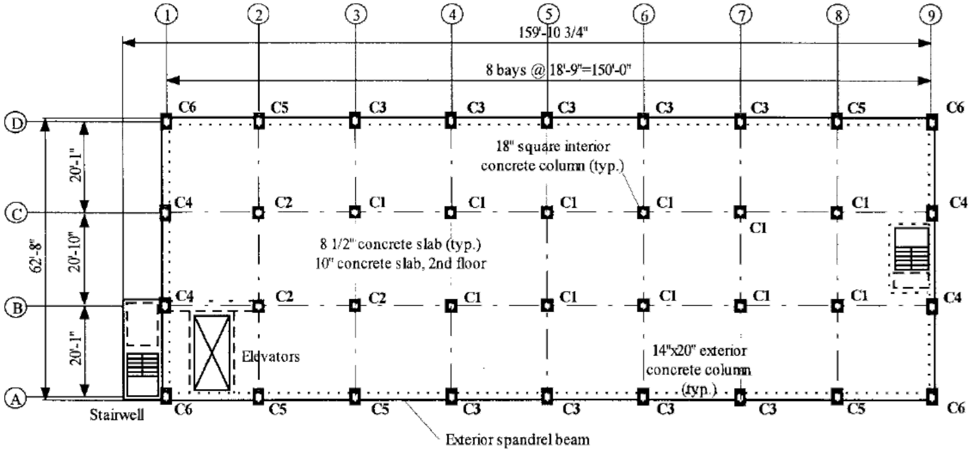
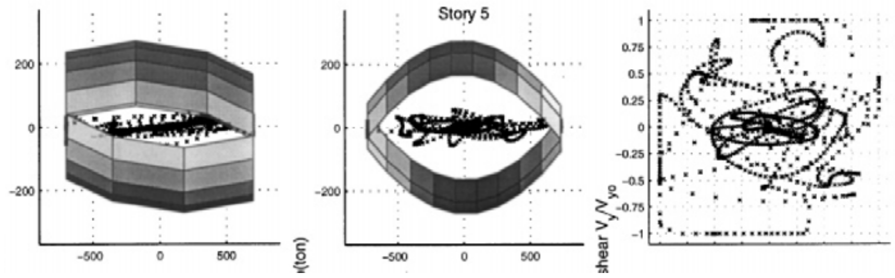
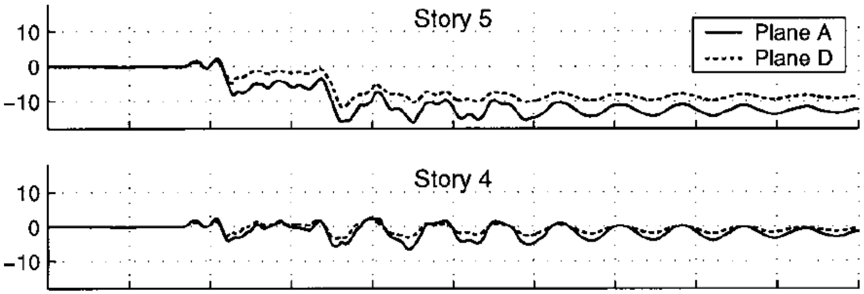
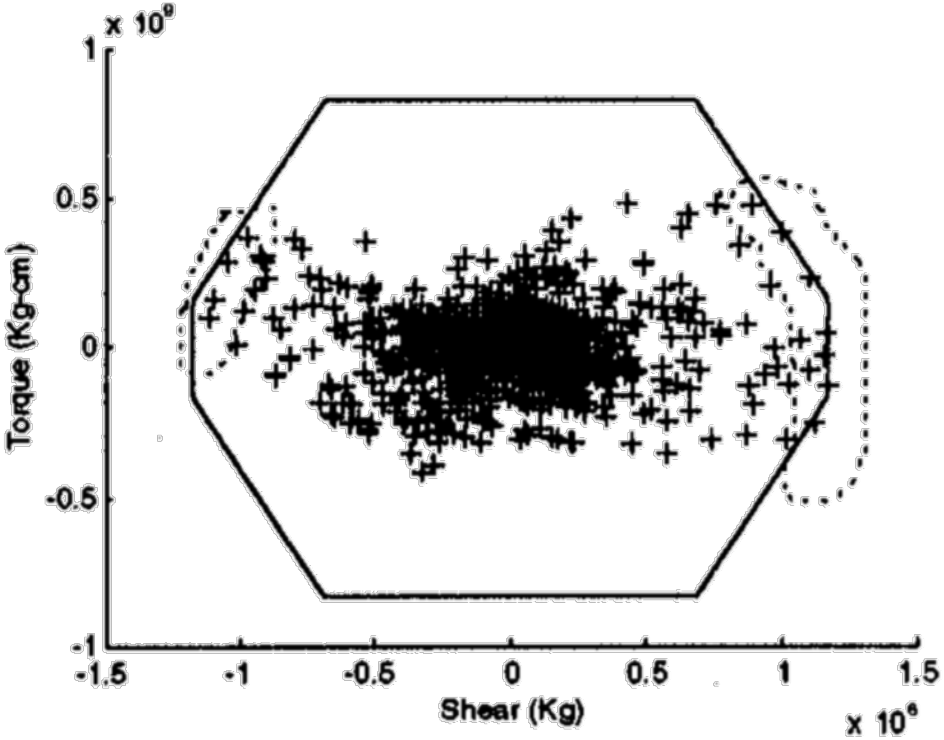


Figure 12. Schematic structural plan of the seven-storey R/C building considered.

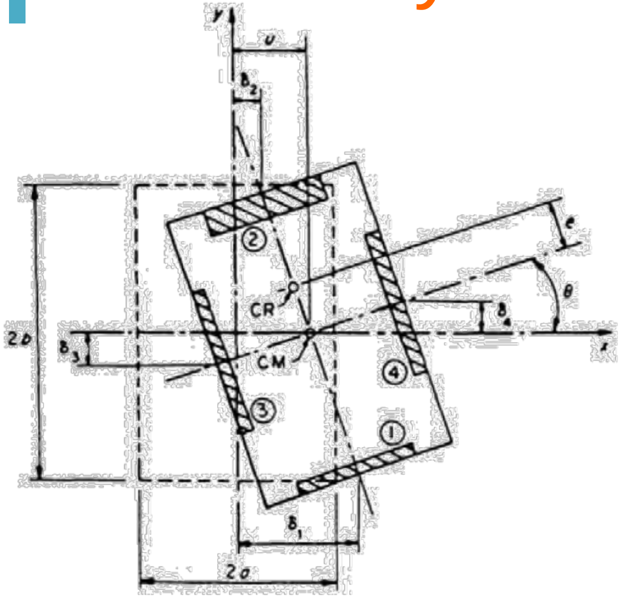


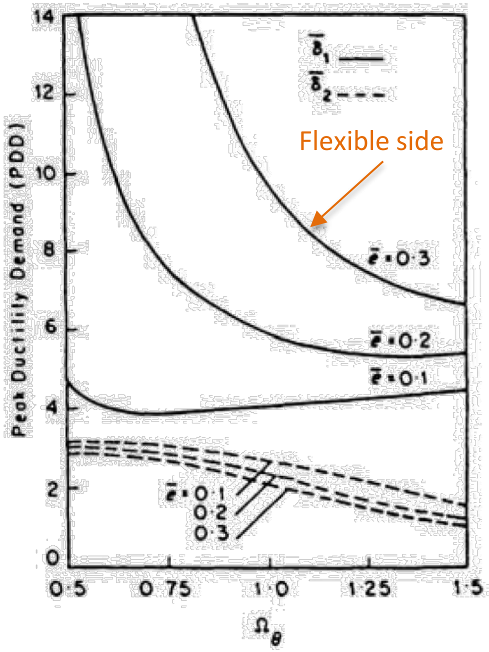


4. Torsion in a nominally symmetric building



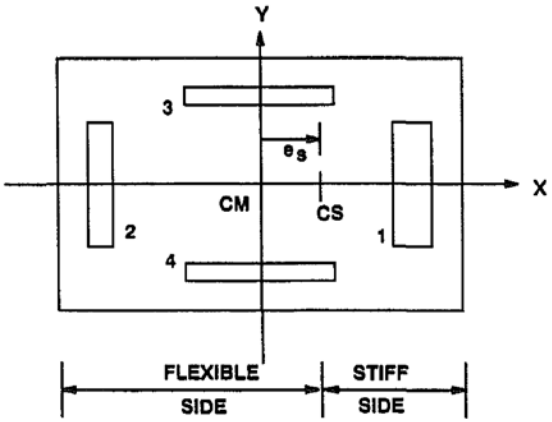
5. Ductility demand

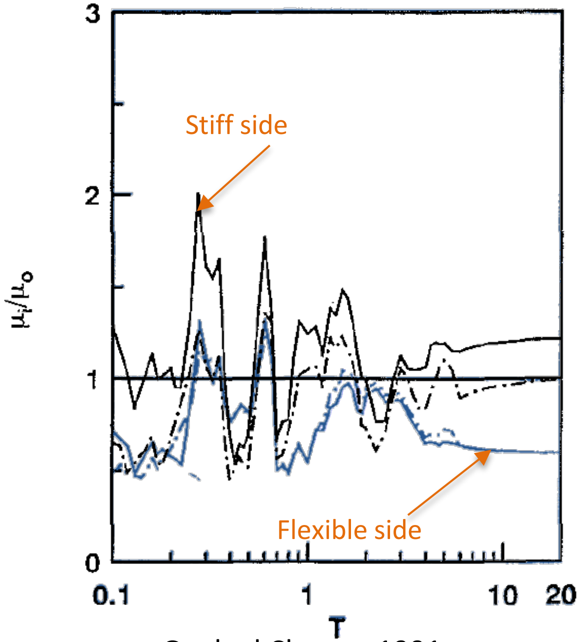




Flexible side

Syamal and Pekau, 1985

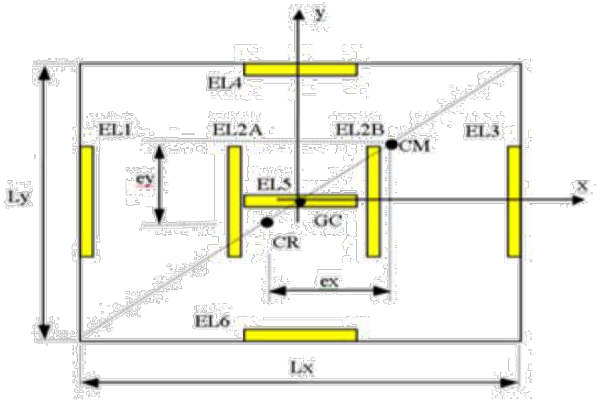




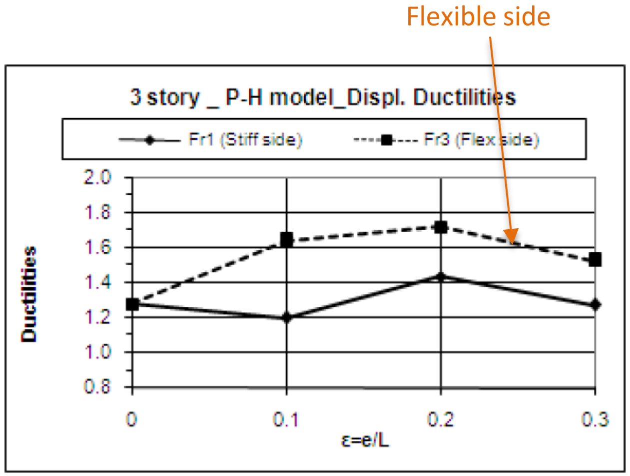
Stiff side

Flexible side

Goel ad Chopra, 1991

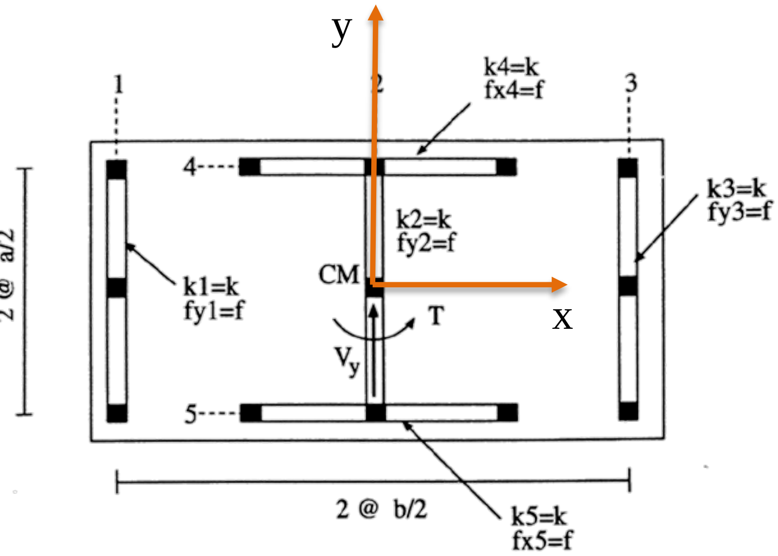


Flexible side



Anagnostopoulos et al., 2015

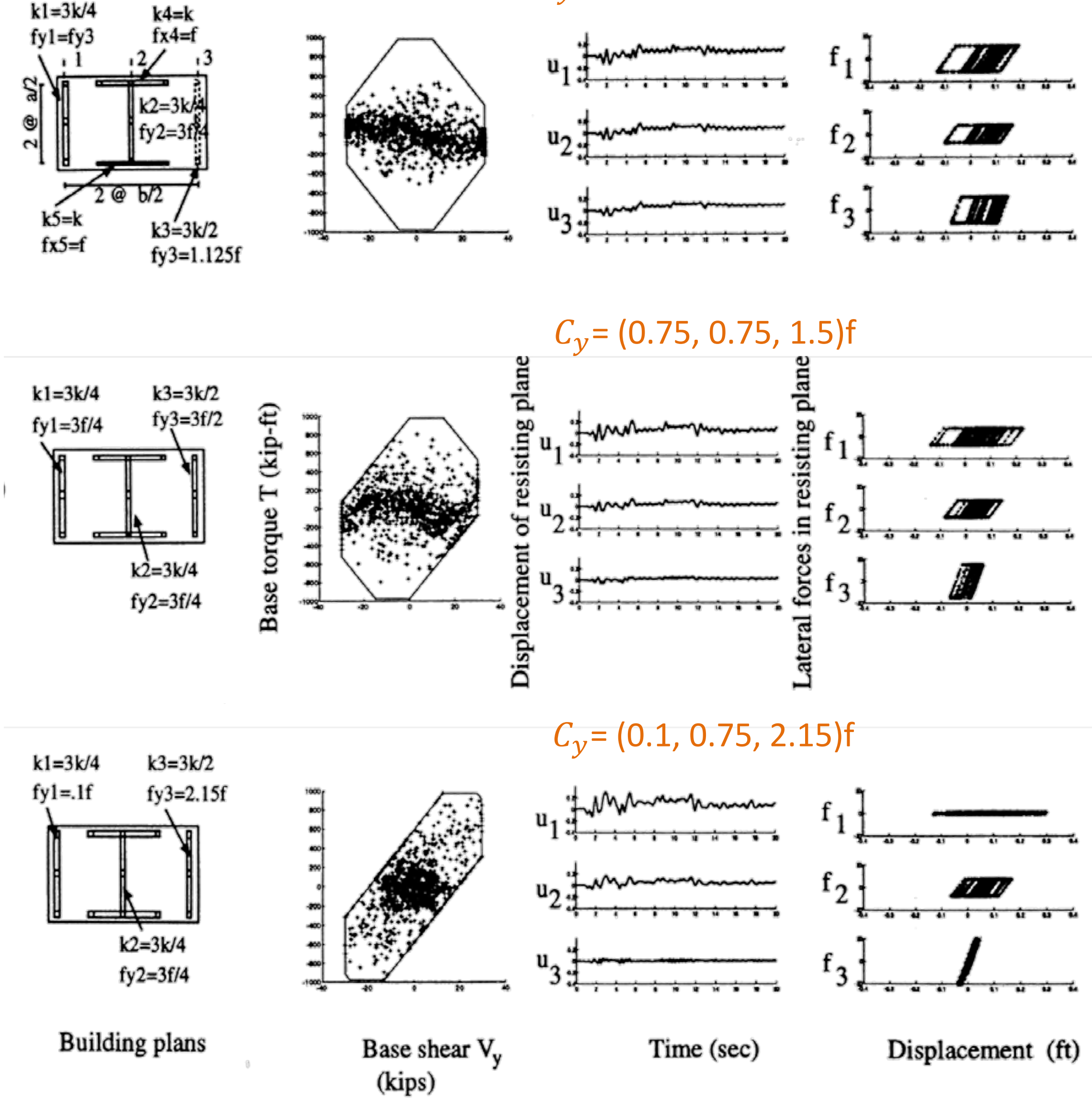
5. Distribution of strength



C_y= (1.125, 0.75, 1.125)f

C_y= (0.75, 0.75, 1.5)f

C_y= (0.1, 0.75, 2.15)f



6. Orthogonal Elements

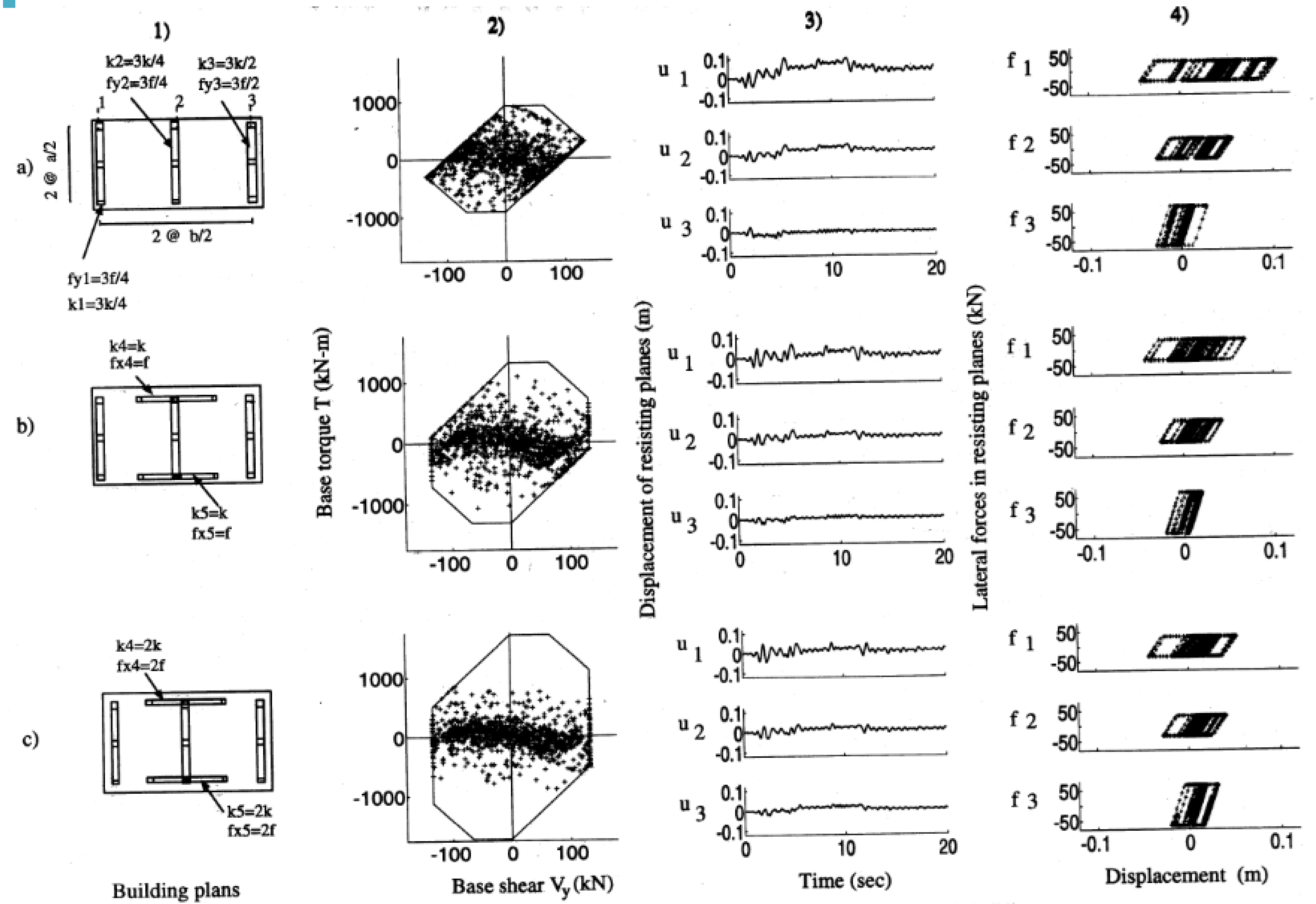
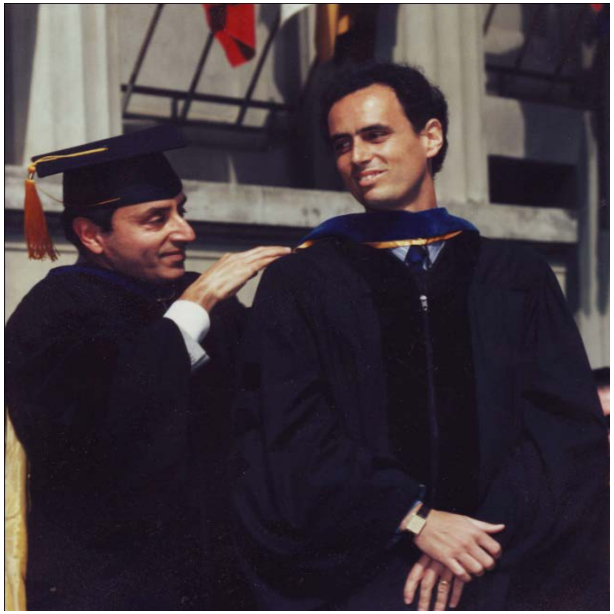
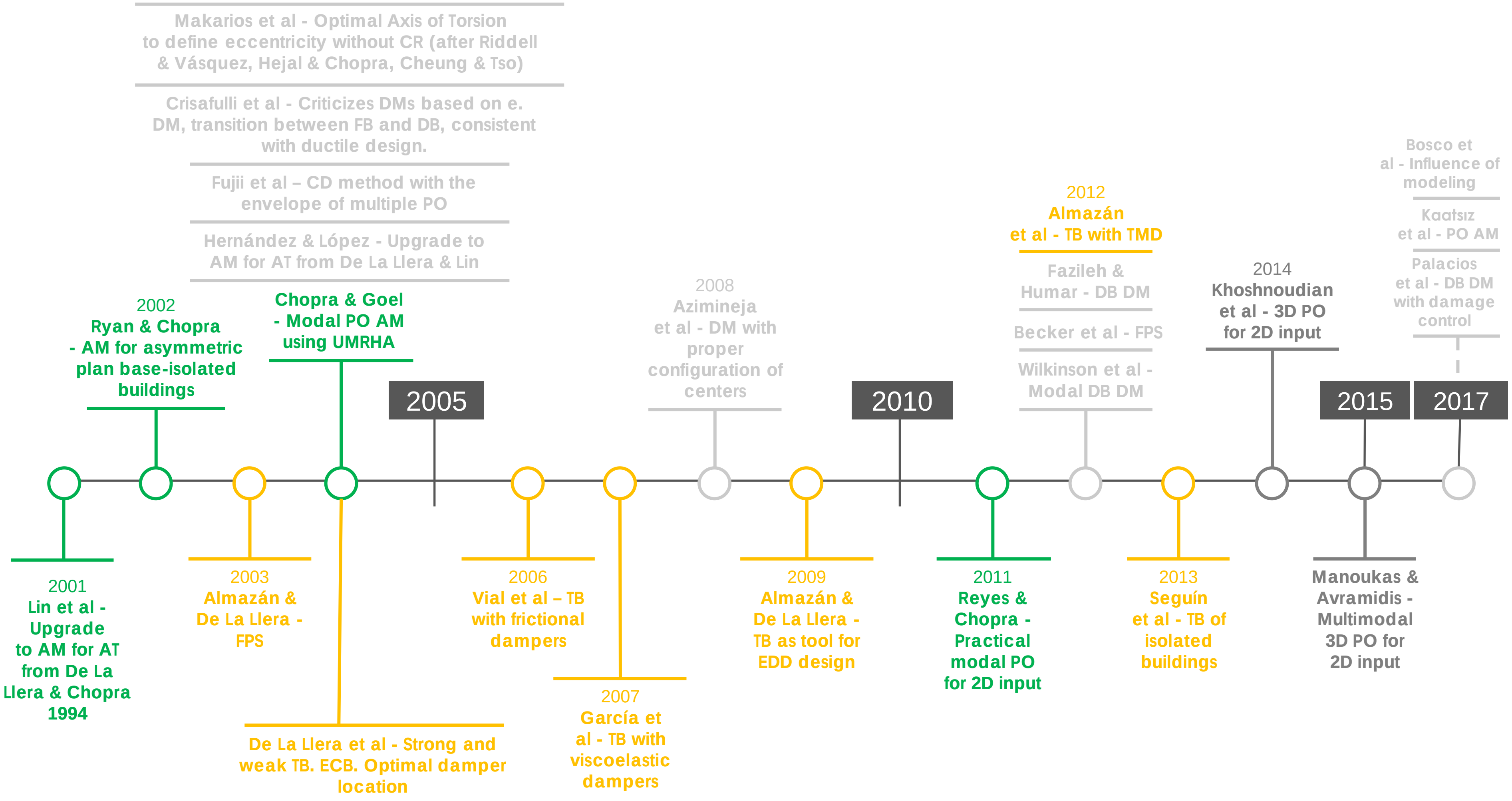


Figure 5. Effect of orthogonal resisting planes on the seismic response of asymmetric buildings

A special moment…



Time Line: Phase III



2001
Lin et al - Upgrade to AM for AT from De La Llera & Chopra 1994

2002
Ryan & Chopra - AM for asymmetric plan base-isolated buildings

2003
Almazán & De La Llera - FPS

Makarios et al - Optimal Axis of Torsion to define eccentricity without CR (after Riddell & Vásquez, Hejal & Chopra, Cheung & Tso)

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2005

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Vial et al – TB with frictional dampers

2007
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2008
Azimineja et al - DM with proper configuration of centers

2009
Almazán & De La Llera - TB as tool for EDD design

2010

2011
Reyes & Chopra - Practical modal PO for 2D input

2012
Almazán et al - TB with TMD

Fazileh & Humar - DB DM

Becker et al - FPS

Wilkinson et al - Modal DB DM

2013
Seguín et al - TB of isolated buildings

2014
Khoshnoudian et al - 3D PO for 2D input

2015

Manoukas & Avramidis - Multimodal 3D PO for 2D input

2017

Bosco et al - Influence of modeling

Kaatsız et al - PO AM

Palacios et al - DB DM with damage control

🟩 Chopra
🟨 Chopra's Influence
⬛ Others
⬜ WCEE

Torsional Control

Seminar AKC

Pushover for asymmetric buildings

Moghadam & Tso, 1996

First approach: Two 3D pushover analyses + dynamic response of equivalent SDOF system

Kilar & Fajfar, 1997

Pseudo-3D pushover with planar macroelements: estimate global plastic mechanism, ductilities, etc.

Fig. 10

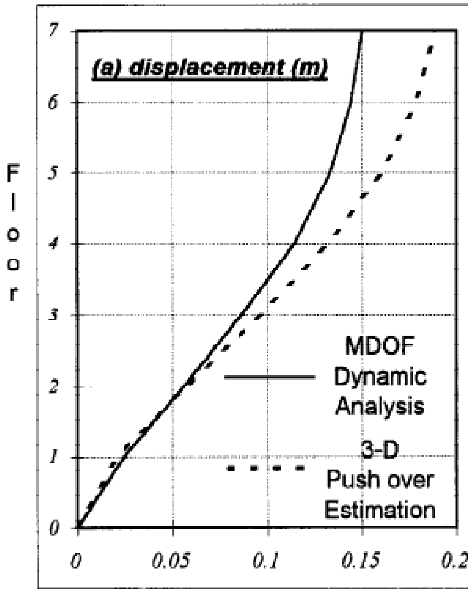


Fig. 11

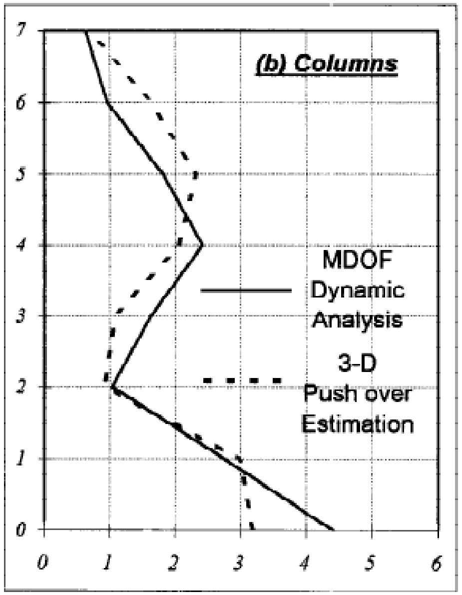
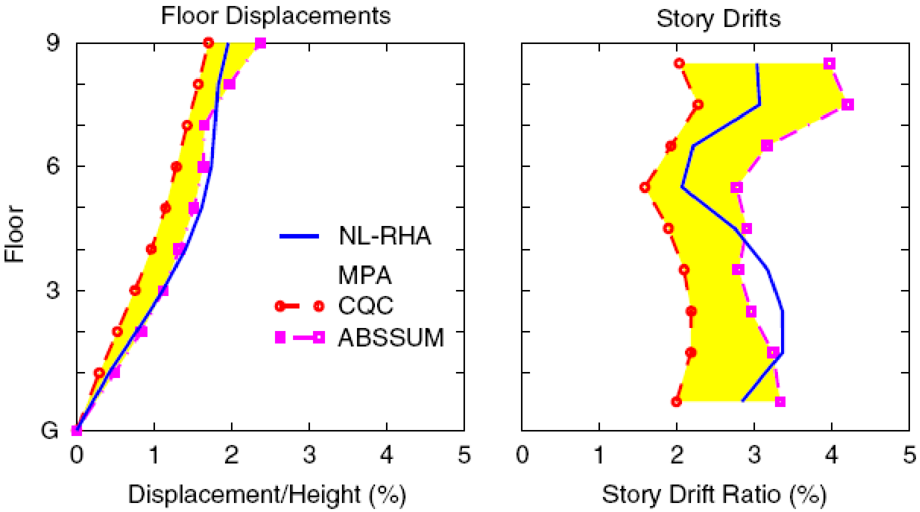


Fig. 10. Maximum displacement and interstorey drift ratio of flexible edge (Whitier EQ record)

Fig. 11. Maximum ductility demands in beams and columns on Frame 3 (Whitier EQ record)

Chopra & Goel, 2004

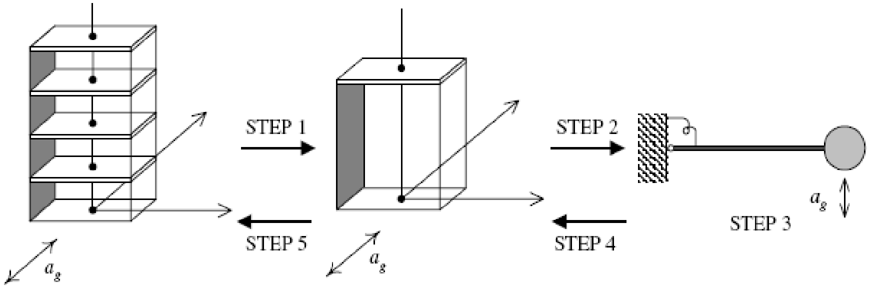
Modal pushover analysis using UMRHA



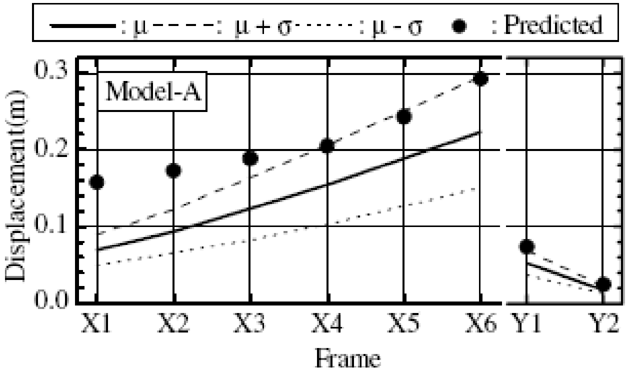
Pushover for asymmetric buildings

Fujii et al, 2004

Simplified method involving pushover of each planar frame, pushover of equivalent SSMs, and capacity-demand spectra of equivalent SDOF models

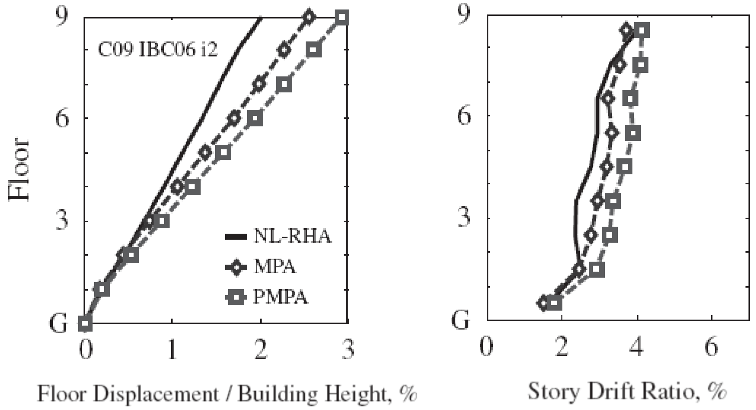


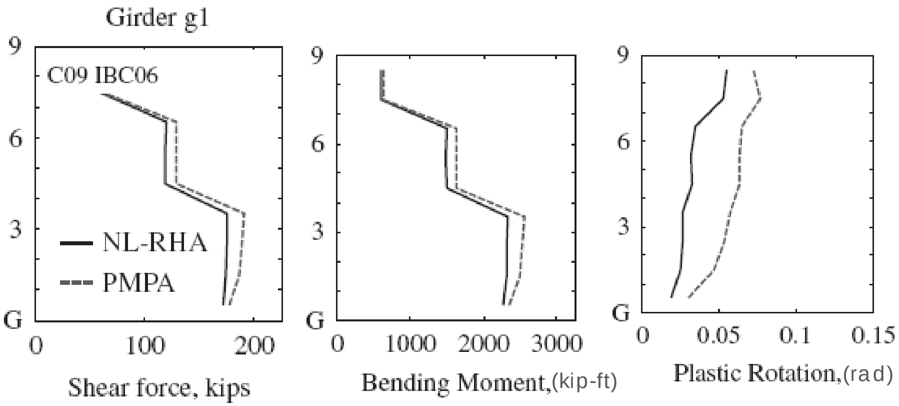
(a) Multi-Story Model (2*N*-DOFs)
(b) Equivalent Single-Story Model (2-DOFs)
(c) Equivalent SDOF Model (1-DOF)



Reyes & Chopra, 2011

Practical MPA (PMPA) is a reliable estimator of nonlinear behavior of asymmetric buildings: tested with structures designed with UBC85, IBC06

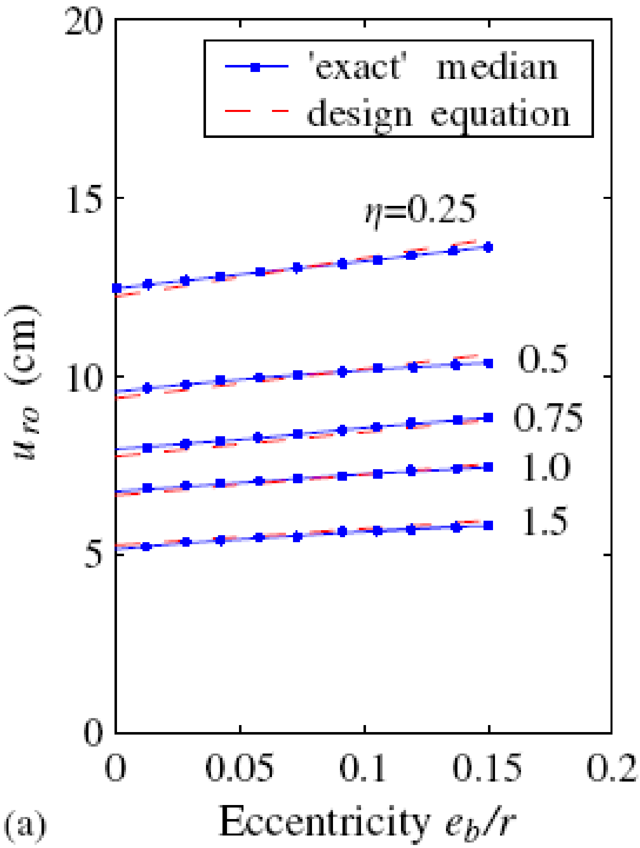




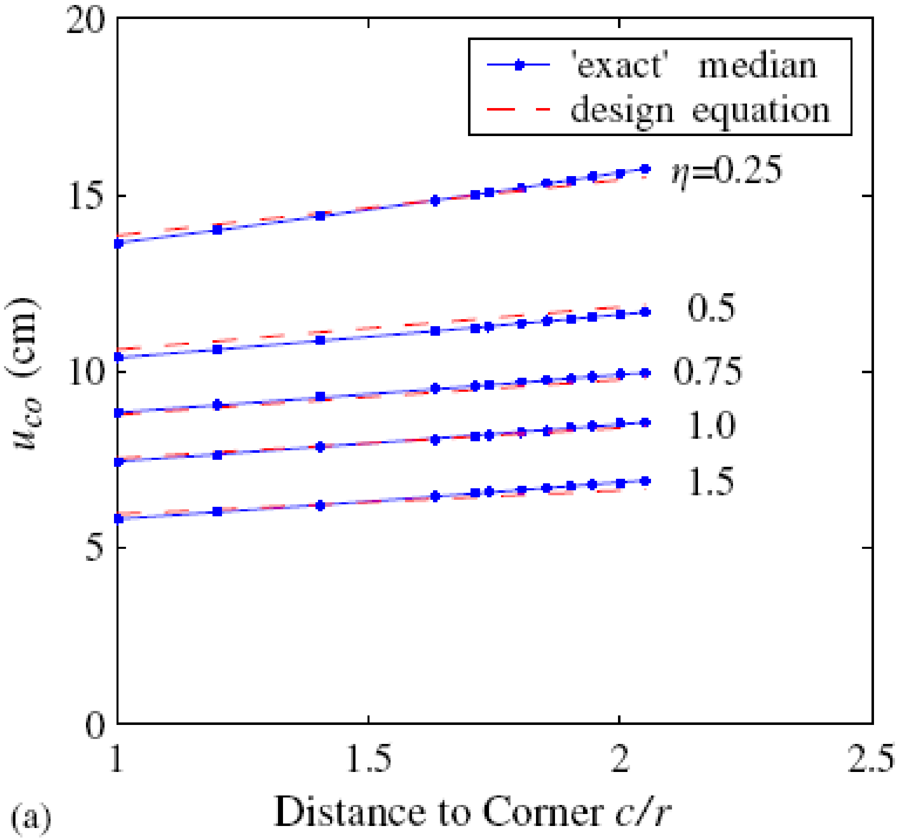
Demand estimation in isolated buildings

Ryan & Chopra, 2004

Method to estimate the peak deformation of isolators in an asymmetric plan buildings



(a)



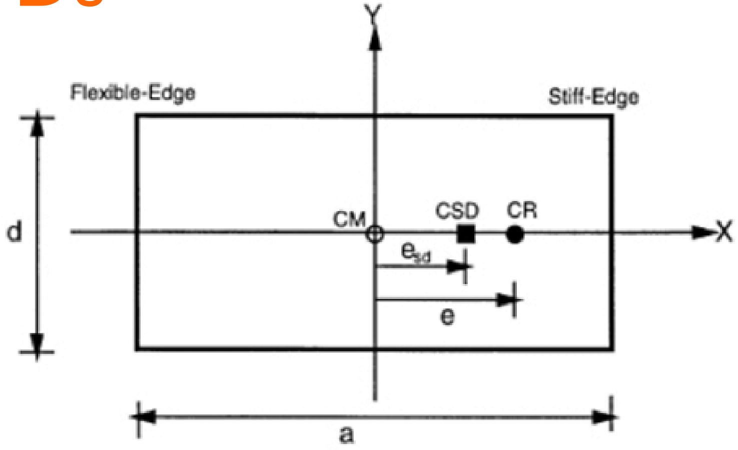
(a)

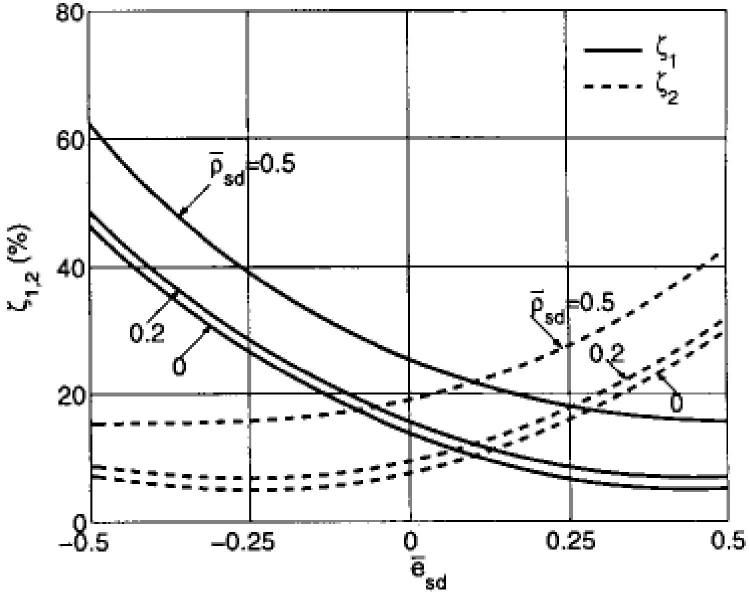
Response control with EDDs

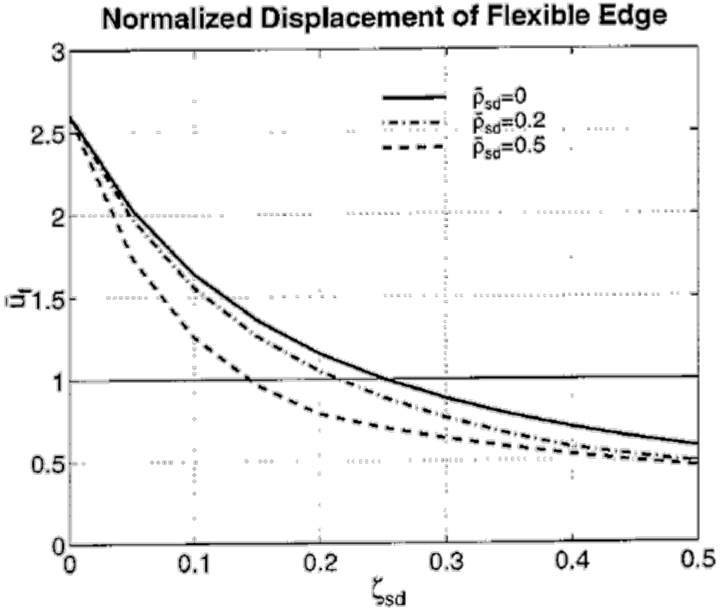
Goel, 1998

Optimal distribution of VDs:

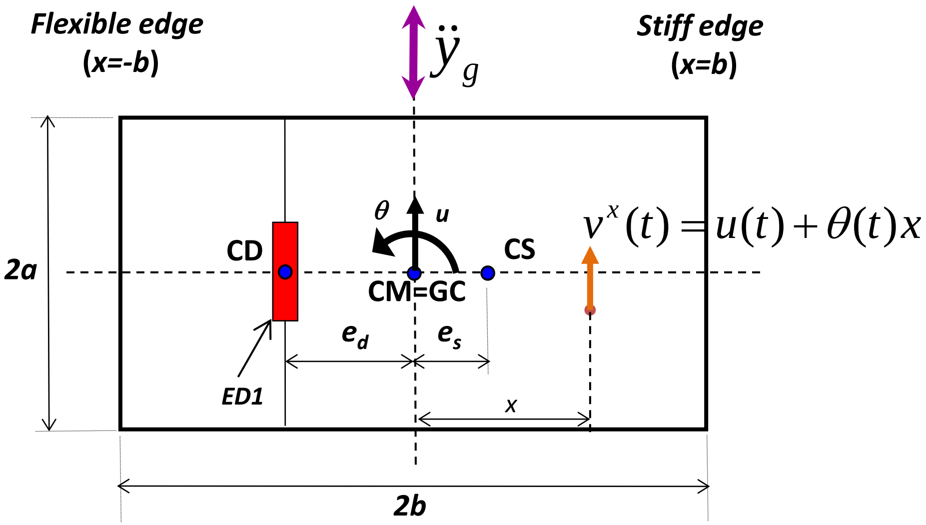
1. Location of the CSD
2. Radius of gyration of EDDs

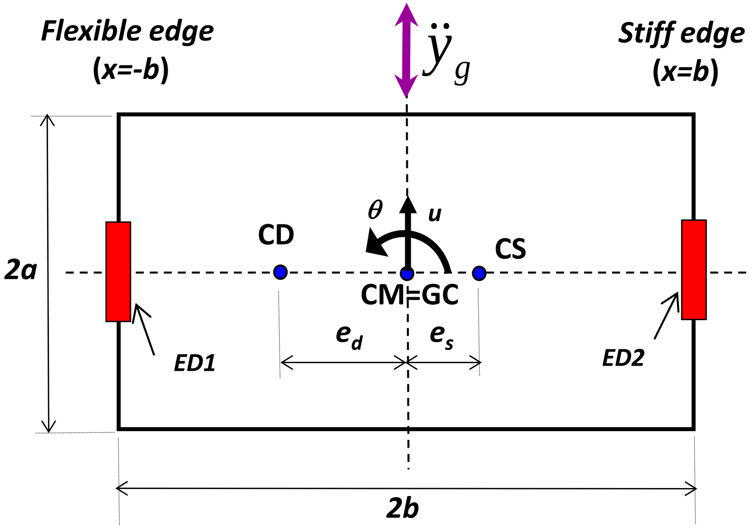






Torsional balance with EDDs





$$E[v_x^2] = E\left[\left(u(t) + x\theta(t)\right)^2\right] = E[u^2] + 2xE[\theta u] + x^2E[\theta^2]$$

$$E\left[v_b^2\right]=E\left[v_{-b}^2\right] \Rightarrow 2bE[\theta(t)u(t)] = -2bE[\theta(t)u(t)] \;\; \Rightarrow E[\theta(t)u(t)]=0,$$

Torsional balance: $\boxed{\text{Search for } e_d \ni \rho_{u\theta} = 0}$

Torsional balance

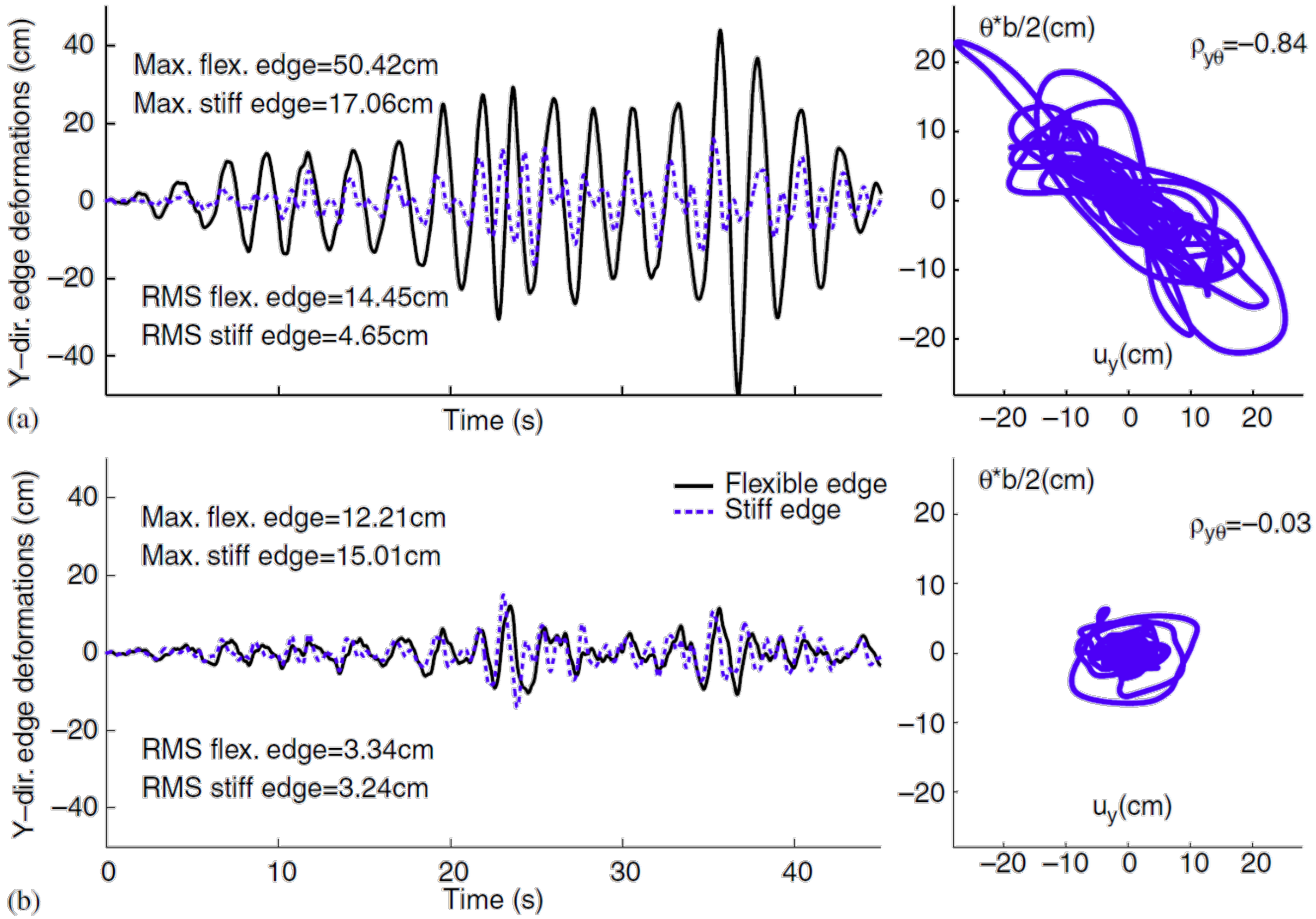


Figure 7. Y-direction edge deformations: (a) bare structure ($T_s = 2s$, $\xi_s = 0.05$, $b/a = 2$, $\Omega_s = 1.3$, $e_s = 0.2b$) and (b) damped structure ($\xi_d = 0.2$, $e_d = -0.25b$) subjected to an artificial record NCh compatible.

Final Comments

Final technical comments

- The contribution of Professor Chopra (and his students) undoubtedly pushed forward the understanding of the complicated response problem of lateral-torsional coupling in buildings;

- The evolution of the modeling and computational capacity has seamlessly solved some of the issues associated with natural torsion; however, seismic codes are still lagging behind in their seismic design provisions for natural torsion;

- Although cumbersome, the $\pm\beta b$ shift of the CM to account for accidental torsion has proven effective in practice;

- The use of massive data analysis, complex inelastic simulations, and uncertainty quantification capacities could still produce some useful results in both domains of building torsion

Final personal comments

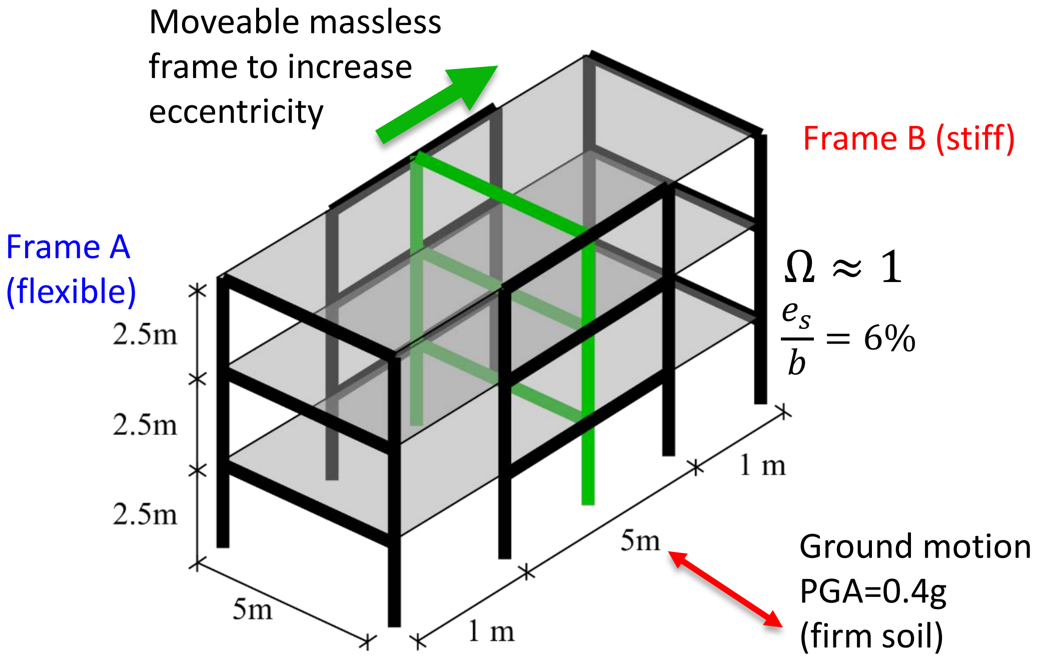
- Professor Chopra was a real mentor teaching me how to do research in the field from scratch—identify the most important from the less important;
- He taught me how to write technical work, and preached me with the example (ENG130);
- He showed me what a mentor means beyond the realm of technical work by paying attention to small details that were relevant to me(us);
- He challenged most of my decisions just to make me reflect, which I think it is a critical component of life;
- He always listened;
- As a result, we built a strong relationship based on mutual trust and friendship

Elastic and Inelastic Building Torsion:

Revisited After 25 Years

Juan C. de la Llera, Oct. 2017

Realistic inelastic behavior



Moveable massless frame to increase eccentricity

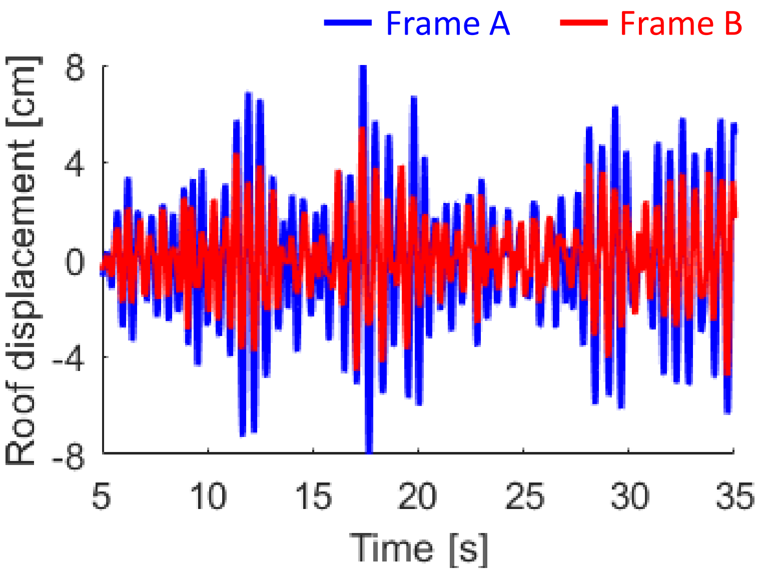
Frame B (stiff)

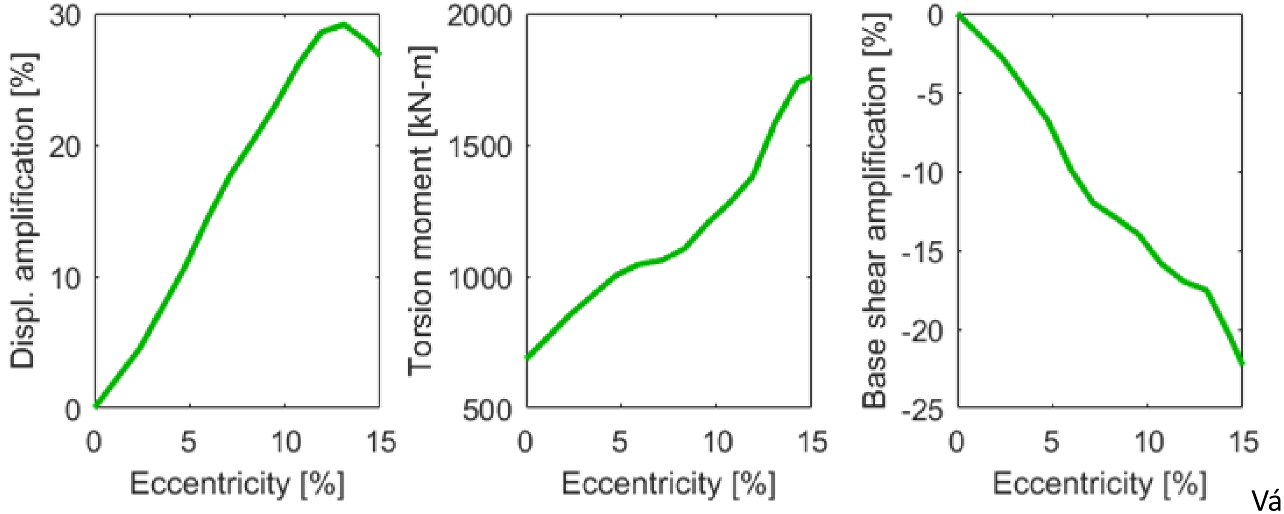
Frame A (flexible)

$\Omega \approx 1$

$\frac{e_s}{b} = 6\%$

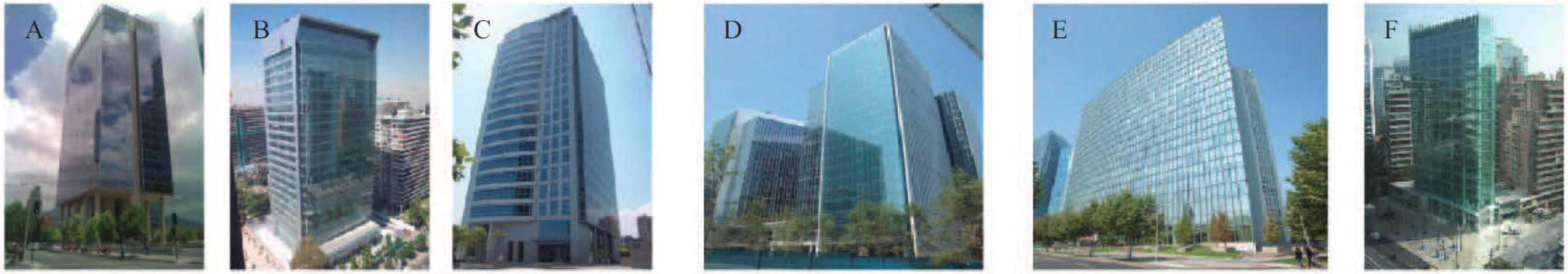
Ground motion
PGA=0.4g
(firm soil)

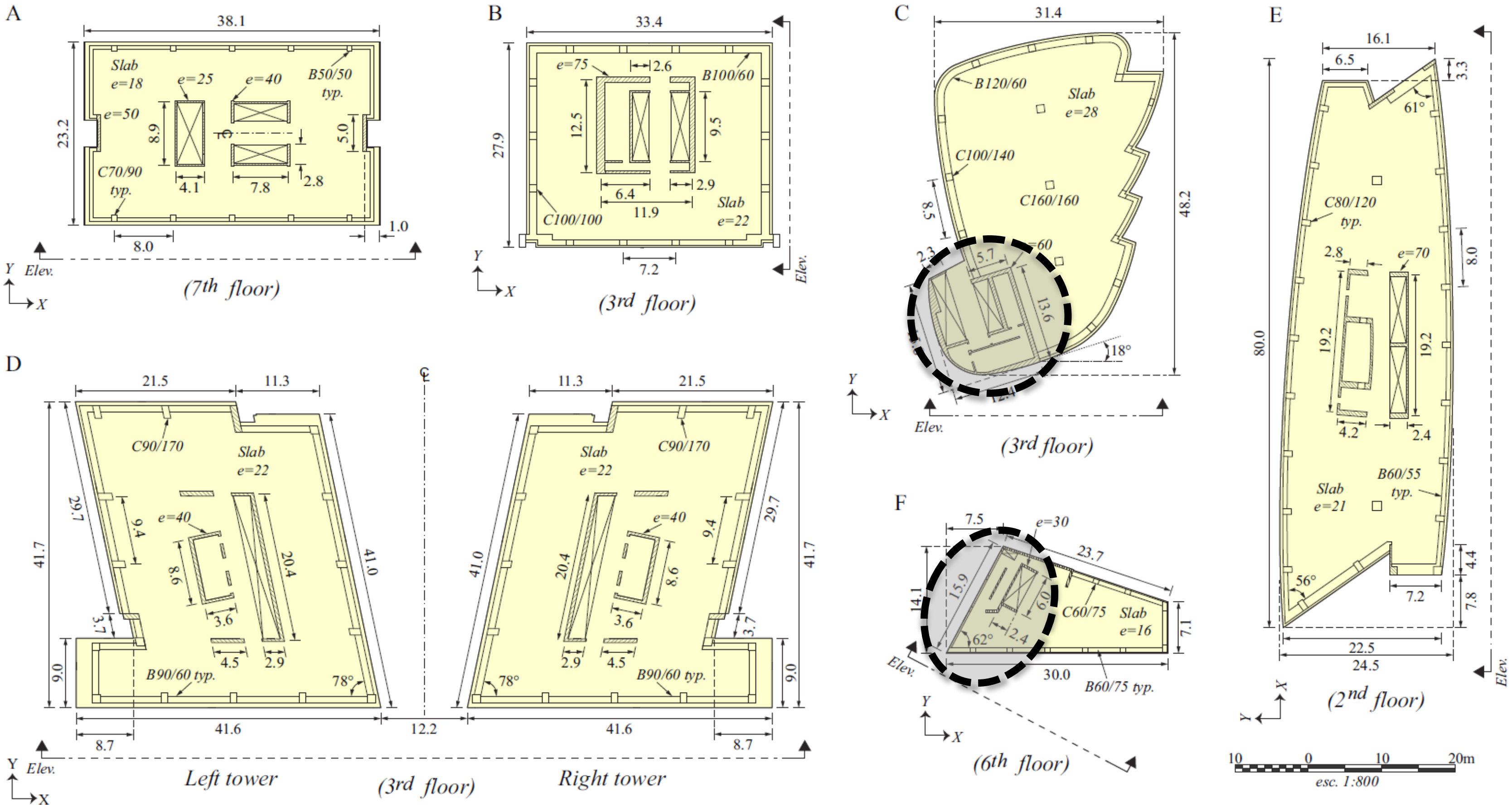




Vásquez J., Muñoz J.P.

Out of our engineering hands





A NATIONAL STRATEGY FOR DISASTER RESILIENCE

1 Resilience

Improve resilience of the country to natural disasters

2 Innovation for Development

Transform the problem of natural disasters into an sustainable innovative advantage for the country

3 Risk and Response

Assess the performance and evaluate the risk of the built, social, and natural environment in a systemic way

4 Physical Processes and Exposure

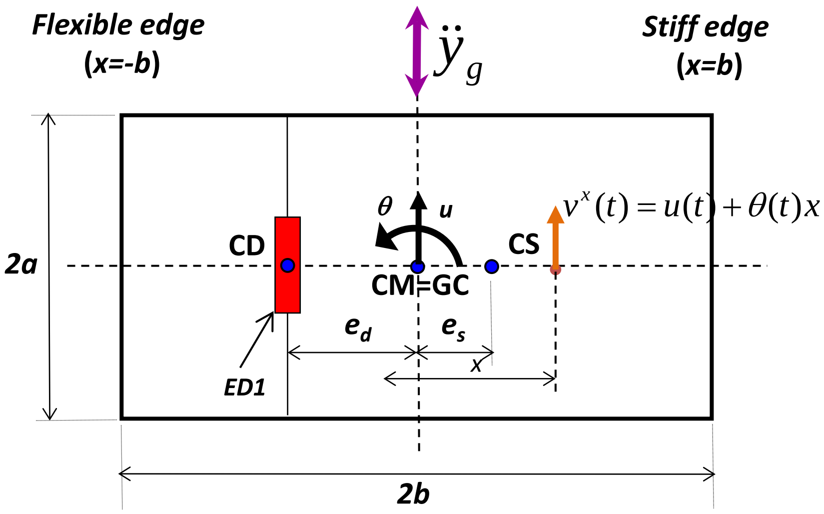
Deepen the understanding of the physical phenomena behind natural disasters and the exposure of the built, social, and natural environments

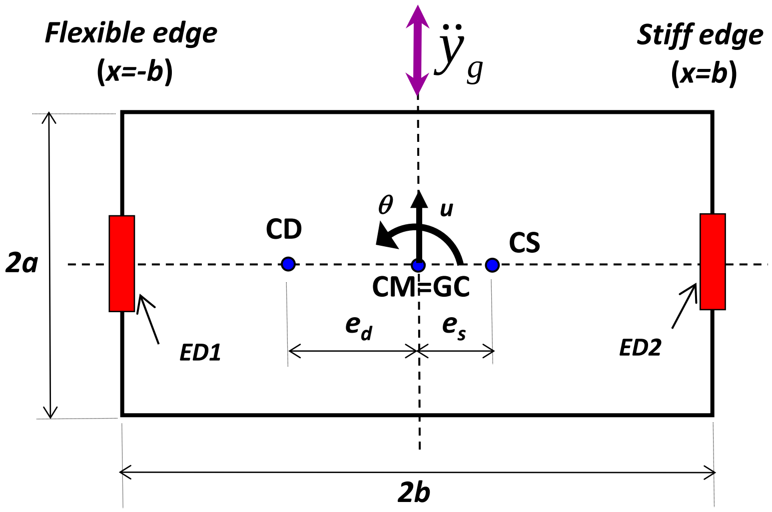
Equations of Motion

Extender al caso más general pero usando notación de torsión

$$\mathbf{M}\ddot{\mathbf{q}}+(\mathbf{C}+\bar{\mathbf{C}})\dot{\mathbf{q}}+\mathbf{K}\mathbf{q}=-\mathbf{M}\mathbf{R}\ddot{y}_{\mathrm{g}}(t)$$

$$\mathbf{M}=m\begin{bmatrix}1 & 0\\ 0 & r^2\end{bmatrix},\quad \mathbf{K}=k_{\mathrm{s}}\begin{bmatrix}1 & e_{\mathrm{s}}\\ e_{\mathrm{s}} & r_{\mathrm{s}}^2+e_{\mathrm{s}}^2\end{bmatrix},\quad \bar{\mathbf{C}}=c_{\mathrm{d}}\begin{bmatrix}1 & e_{\mathrm{d}}\\ e_{\mathrm{d}} & r_{\mathrm{d}}^2+e_{\mathrm{d}}^2\end{bmatrix}$$





3. Centers of the Structure

Hejal & Chopra, 1987

Same conclusions as in Cheung & Tso. For a special class of buildings, the elements have proportional lateral stiffness matrices.

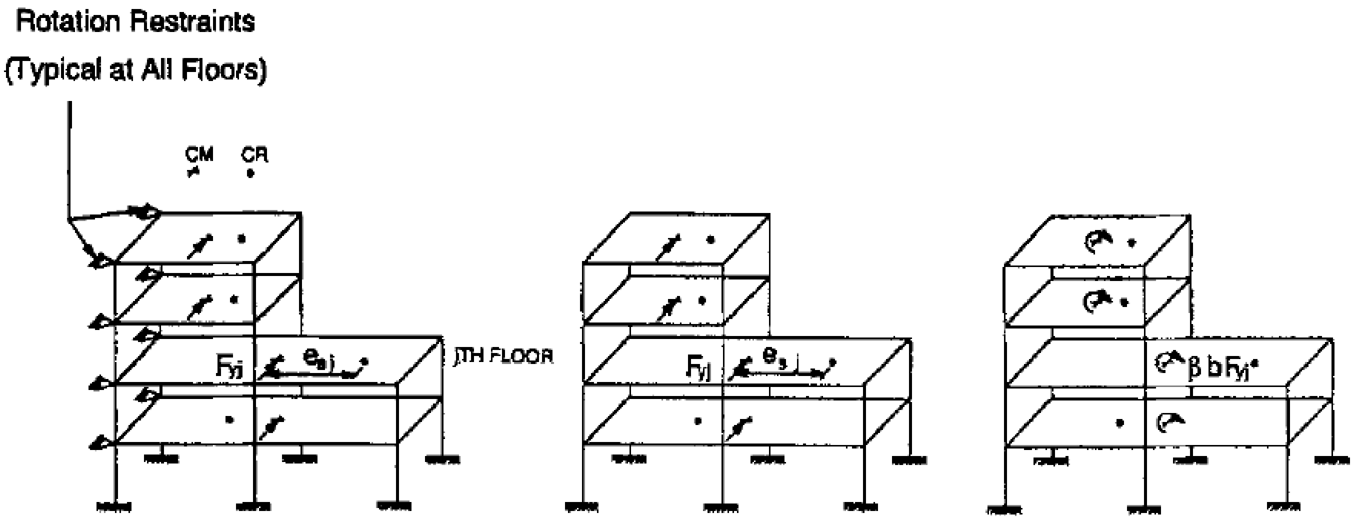
Similarity between one-story buildings and this special class.

Hejal & Chopra, 1989

Due to the similarity and by extending the work of Kan & Chopra (1977) it is possible to compute the response of a **TCMSB** by analyzing both the associated **TUMSB and TCSSB**.

Goel & Chopra, 1993

Design method without locating centers of rigidity. The procedure combines the results of 3 analyses.



(a) Step 1

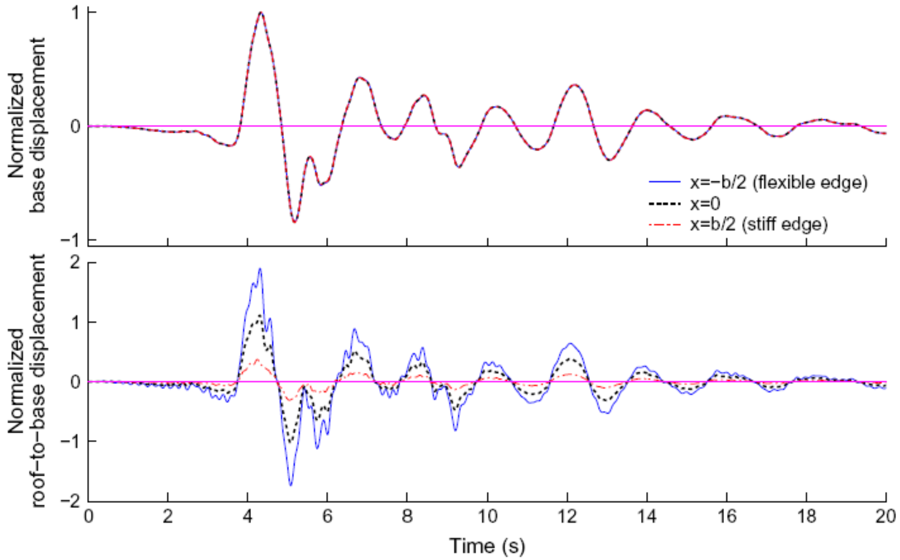
(b) Step 2

(c) Step 3

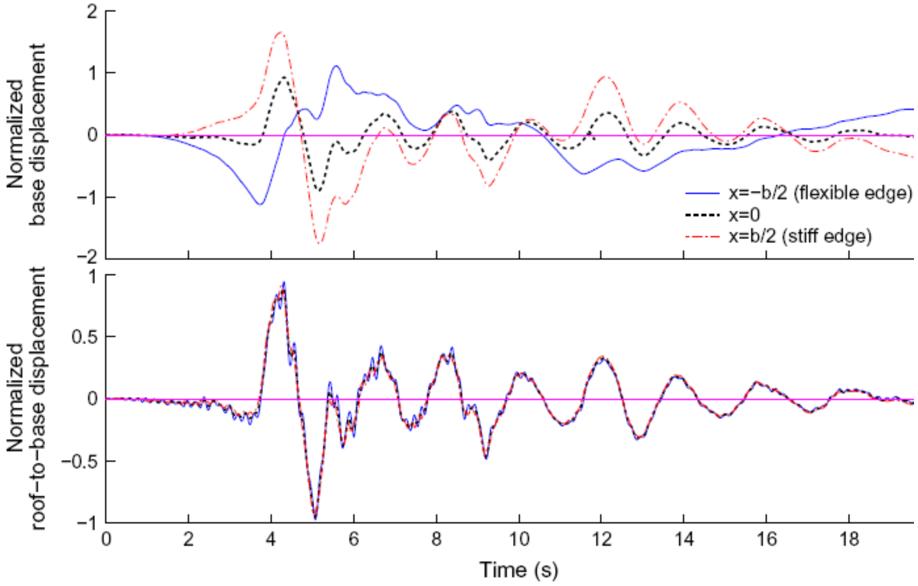
Torsional control

Seguín et al, 2013

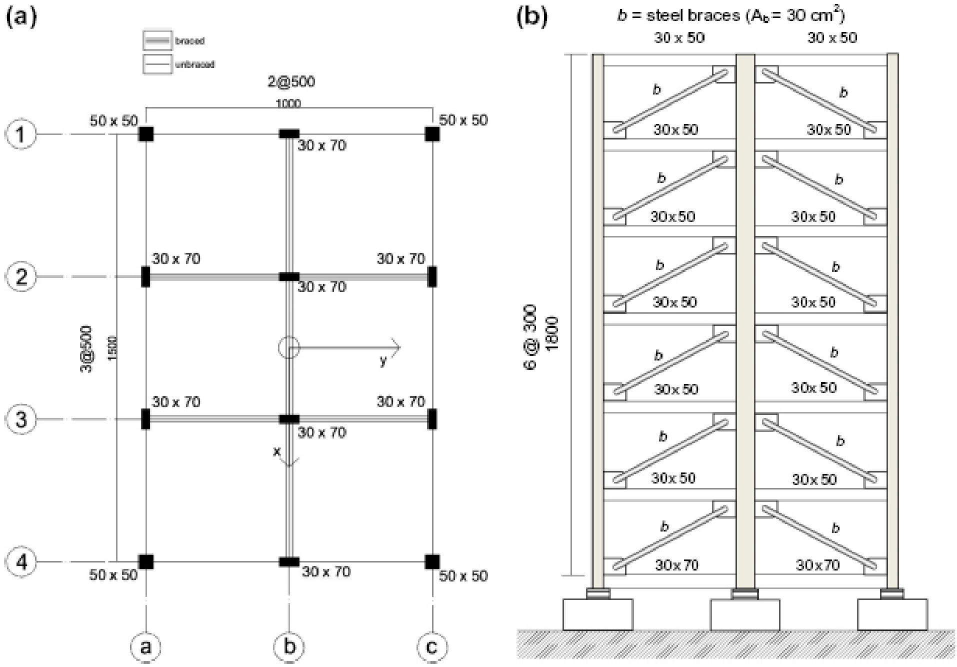
Method for optimal torsional control of the superstructure, at expense of introducing torsion in the isolation base, using two torsional balance criterion



(a) $\hat{e}^{(b)} = 0, \Omega_o^{(b)} = 1.0$



(b) $\hat{e}^{(b)} = \hat{e}^{(s)} = 0.25, \Omega_o^{(b)} = 0.2$



2. Energy Dissipation Devices

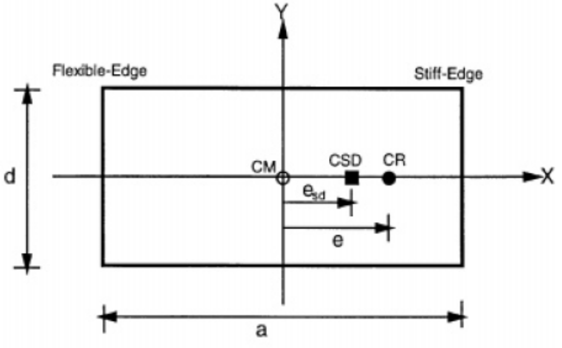
Goel, 1998

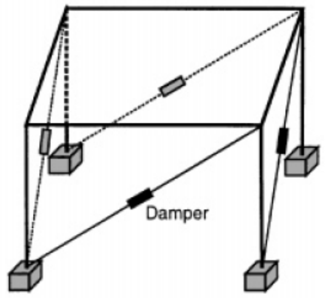
Viscous dampers optimal distribution:

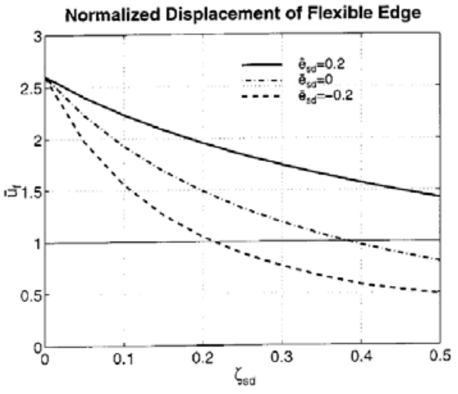
1. Location of the CSD
2. Radius of gyration of EDDs

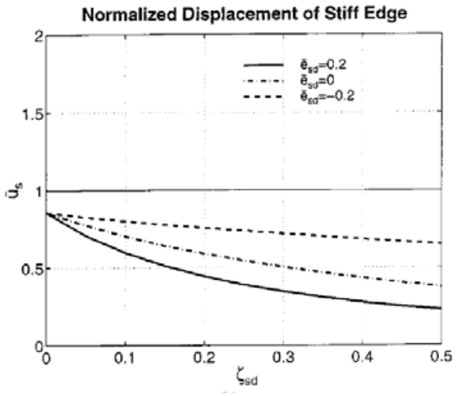
Almazán et al, 2012

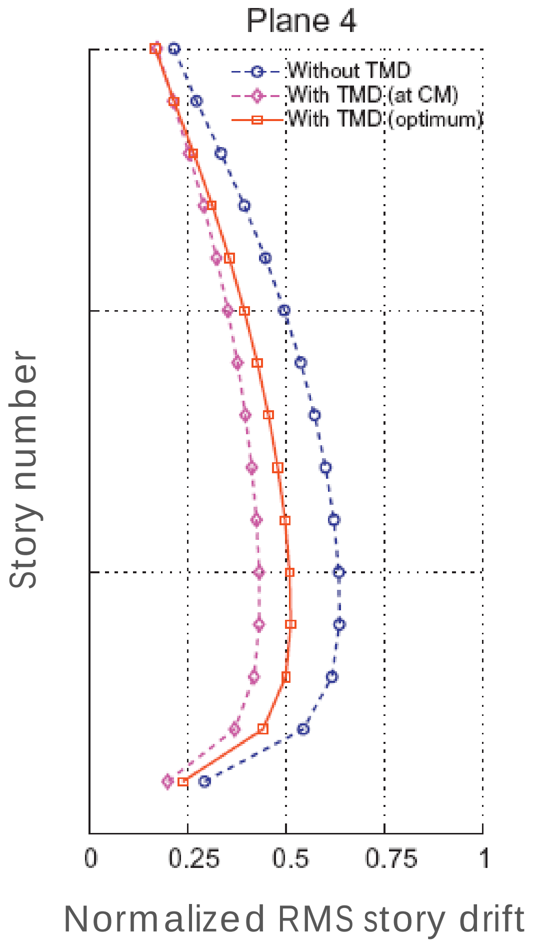
A **TMD** can be optimally designed to control the torsional response and **reduce the RMS story drifts**



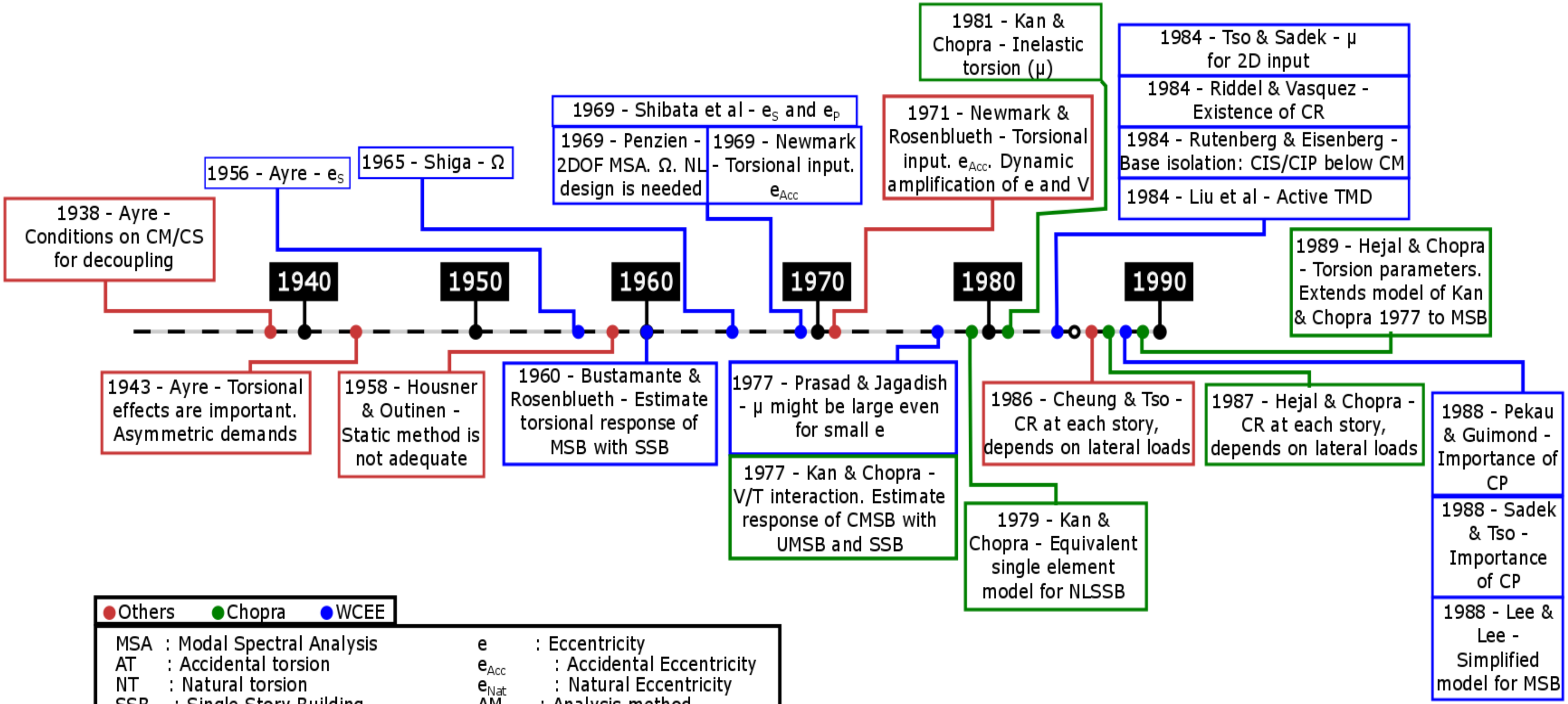



Normalized Displacement of Flexible Edge


Normalized Displacement of Stiff Edge


Plane 4

History: 1930 – 1990



1938 - Ayre - Conditions on CM/CS for decoupling

1943 - Ayre - Torsional effects are important. Asymmetric demands

1956 - Ayre - e_S

1958 - Housner & Outinen - Static method is not adequate

1960 - Bustamante & Rosenblueth - Estimate torsional response of MSB with SSB

1965 - Shiga - Ω

1969 - Shibata et al - e_S and e_P

1969 - Penzien - 2DOF MSA. Ω. NL design is needed

1969 - Newmark - Torsional input. e_{Acc}

1971 - Newmark & Rosenblueth - Torsional input. e_{Acc}. Dynamic amplification of e and V

1977 - Prasad & Jagadish - μ might be large even for small e

1977 - Kan & Chopra - V/T interaction. Estimate response of CMSB with UMSB and SSB

1979 - Kan & Chopra - Equivalent single element model for NLSSB

1981 - Kan & Chopra - Inelastic torsion (μ)

1984 - Tso & Sadek - μ for 2D input

1984 - Riddel & Vasquez - Existence of CR

1984 - Rutenberg & Eisenberg - Base isolation: CIS/CIP below CM

1984 - Liu et al - Active TMD

1986 - Cheung & Tso - CR at each story, depends on lateral loads

1987 - Hejal & Chopra - CR at each story, depends on lateral loads

1988 - Pekau & Guimond - Importance of CP

1988 - Sadek & Tso - Importance of CP

1988 - Lee & Lee - Simplified model for MSB

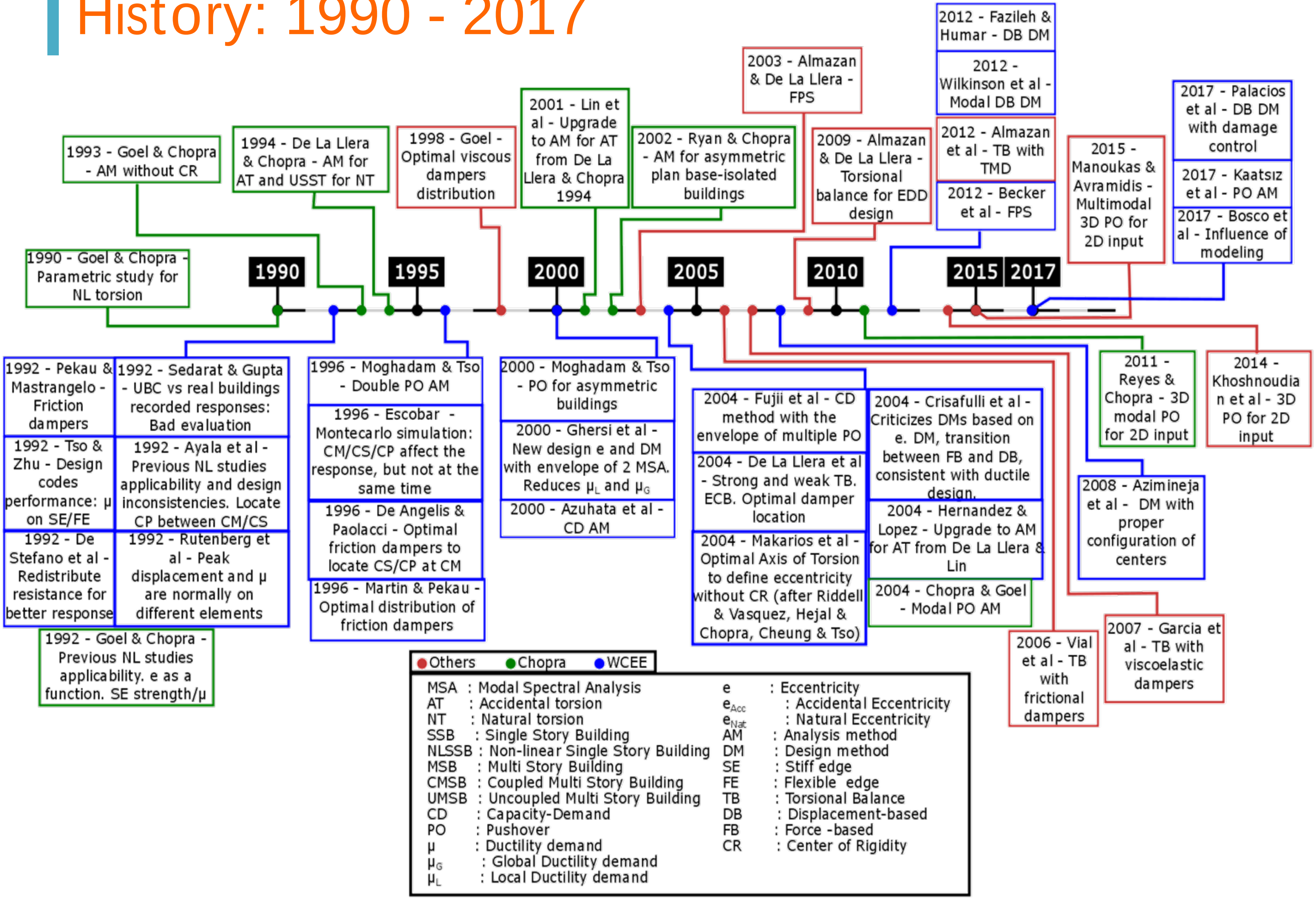
1989 - Hejal & Chopra - Torsion parameters. Extends model of Kan & Chopra 1977 to MSB

● Others ● Chopra ● WCEE

MSA : Modal Spectral Analysis
AT : Accidental torsion
NT : Natural torsion
SSB : Single Story Building
NLSSB : Non-linear Single Story Building
MSB : Multi Story Building
CMSB : Coupled Multi Story Building
UMSB : Uncoupled Multi Story Building
CD : Capacity-Demand
PO : Pushover
μ : Ductility demand
μ_G : Global Ductility demand
μ_L : Local Ductility demand

e : Eccentricity
e_{Acc} : Accidental Eccentricity
e_{Nat} : Natural Eccentricity
AM : Analysis method
DM : Design method
SE : Stiff edge
FE : Flexible edge
TB : Torsional Balance
DB : Displacement-based
FB : Force -based
CR : Center of Rigidity

History: 1990 - 2017



1990 - Goel & Chopra - Parametric study for NL torsion

1992 - Pekau & Mastrangelo - Friction dampers

1992 - Tso & Zhu - Design codes performance: μ on SE/FE

1992 - De Stefano et al - Redistribute resistance for better response

1992 - Goel & Chopra - Previous NL studies applicability. e as a function. SE strength/μ

1992 - Sedarat & Gupta - UBC vs real buildings recorded responses: Bad evaluation

1992 - Ayala et al - Previous NL studies applicability and design inconsistencies. Locate CP between CM/CS

1992 - Rutenberg et al - Peak displacement and μ are normally on different elements

1993 - Goel & Chopra - AM without CR

1994 - De La Llera & Chopra - AM for AT and USST for NT

1996 - Moghadam & Tso - Double PO AM

1996 - Escobar - Montecarlo simulation: CM/CS/CP affect the response, but not at the same time

1996 - De Angelis & Paolacci - Optimal friction dampers to locate CS/CP at CM

1996 - Martin & Pekau - Optimal distribution of friction dampers

1998 - Goel - Optimal viscous dampers distribution

2000 - Moghadam & Tso - PO for asymmetric buildings

2000 - Ghersi et al - New design e and DM with envelope of 2 MSA. Reduces μ_L and μ_G

2000 - Azuhata et al - CD AM

2001 - Lin et al - Upgrade to AM for AT from De La Llera & Chopra 1994

2002 - Ryan & Chopra - AM for asymmetric plan base-isolated buildings

2003 - Almazan & De La Llera - FPS

2004 - Fujii et al - CD method with the envelope of multiple PO

2004 - De La Llera et al - Strong and weak TB. ECB. Optimal damper location

2004 - Makarios et al - Optimal Axis of Torsion to define eccentricity without CR (after Riddell & Vasquez, Hejal & Chopra, Cheung & Tso)

2004 - Crisafulli et al - Criticizes DMs based on e. DM, transition between FB and DB, consistent with ductile design.

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2012 - Fazileh & Humar - DB DM

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2014 - Khoshnoudian et al - 3D PO for 2D input

2015 - Manoukas & Avramidis - Multimodal 3D PO for 2D input

2017 - Palacios et al - DB DM with damage control

2017 - Kaatsız et al - PO AM

2017 - Bosco et al - Influence of modeling

● Others ● Chopra ● WCEE

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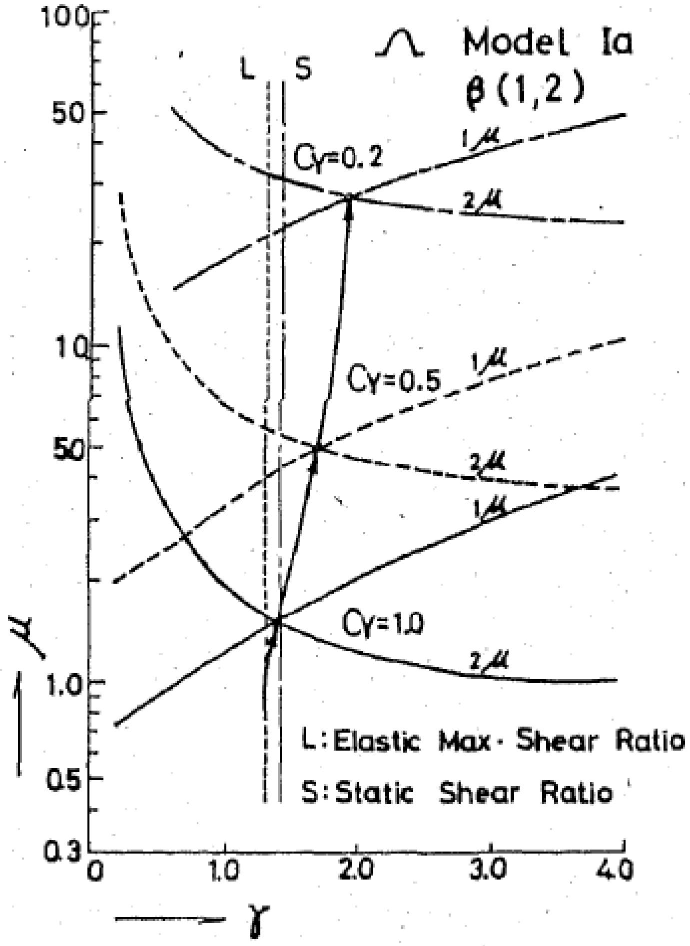
AM : Analysis method
DM : Design method
SE : Stiff edge
FE : Flexible edge
TB : Torsional Balance
DB : Displacement-based
FB : Force -based
CR : Center of Rigidity

Conclusions

5. Ductility Demand

Different demands on both edges implies different designs: need of estimating **ductility demands to guarantee proper ductile design**



Shibata et al, 1969

Dependence of ductility demands on strength distribution

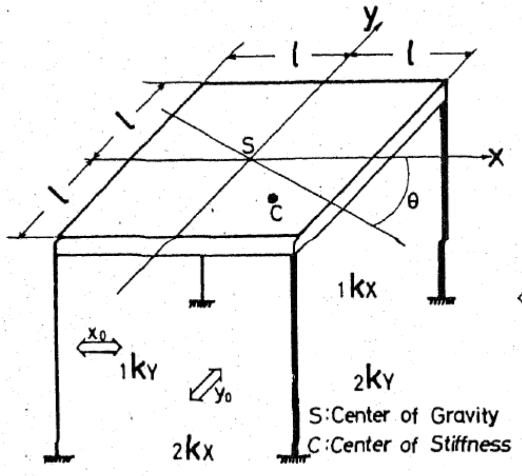


Fig.1 Single-Story Unsymmetrical Building

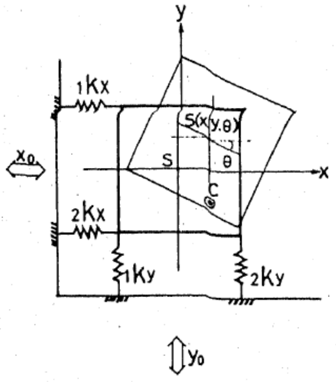


Fig.2 Torsional Vibration Model

Energy Dissipation Devices

Pekau & Mastrangelo, 1992

Optimal **friction dampers** design to reduce the **displacement and ductility demands**

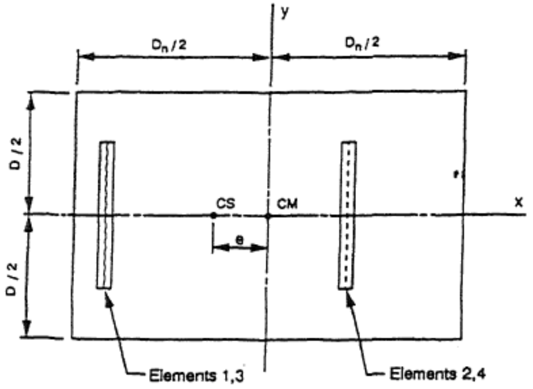
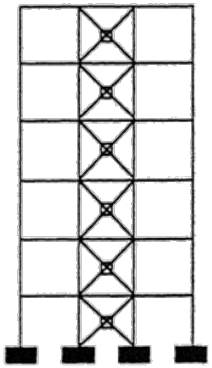


Figure 2. One-story model of friction damped asymmetric structure.



(b) Typical Frame with Friction Damped Bracing

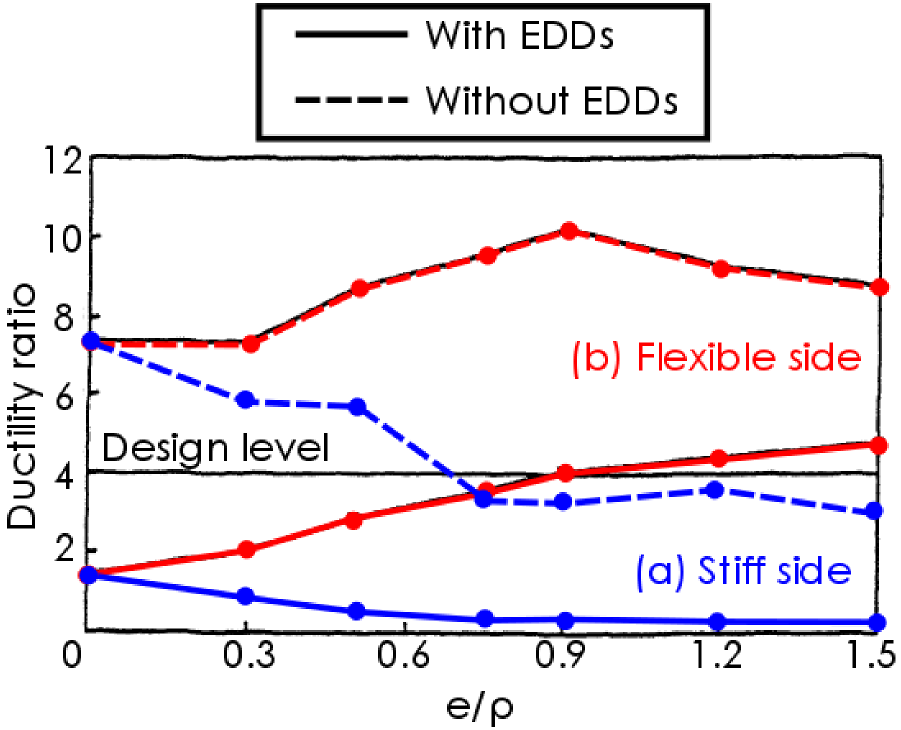
Figure 1. Friction damped bracing in frame structure

Elements:

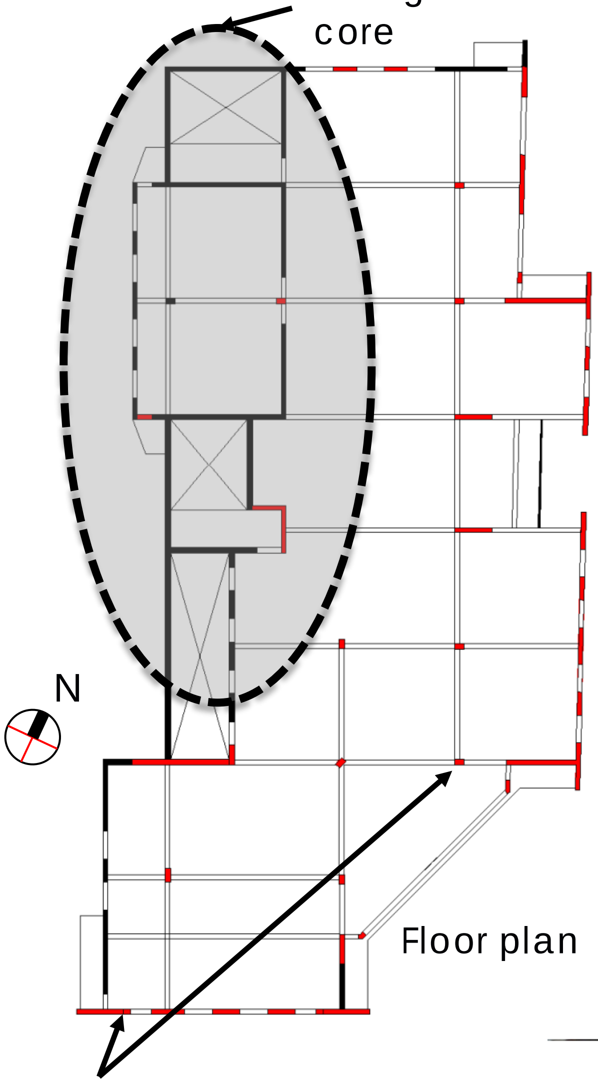
- 1, 2: Frames
- 3, 4: EDDs

De Angelis & Paolacci, 1996

Friction dampers can be optimally designed to **move the CR and CP to the CM**, which **reduces and uniforms damage.**



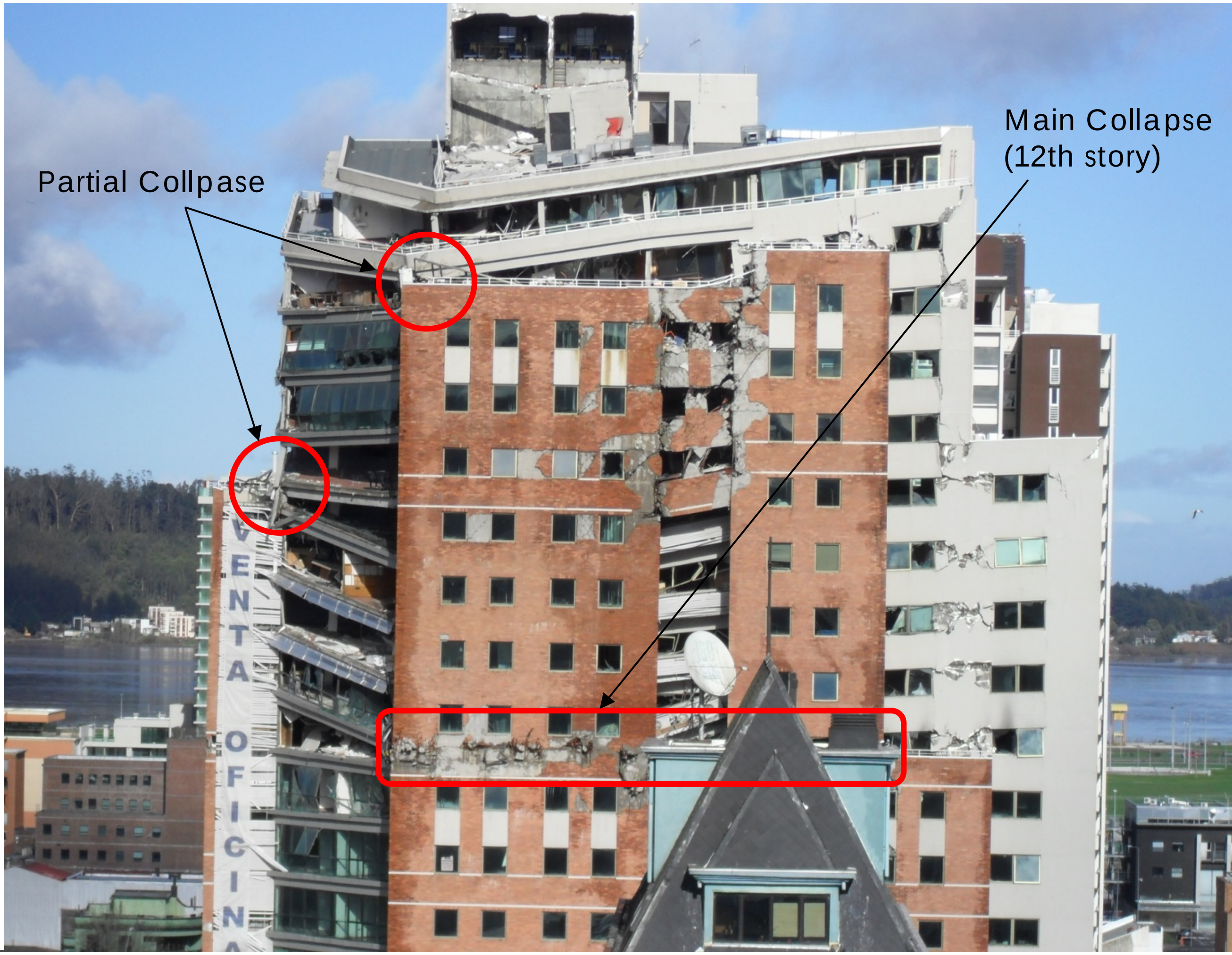
Torsional response, Chile (2010)



Strong core

Floor plan

Extensive wall and column damage



Partial Collpase

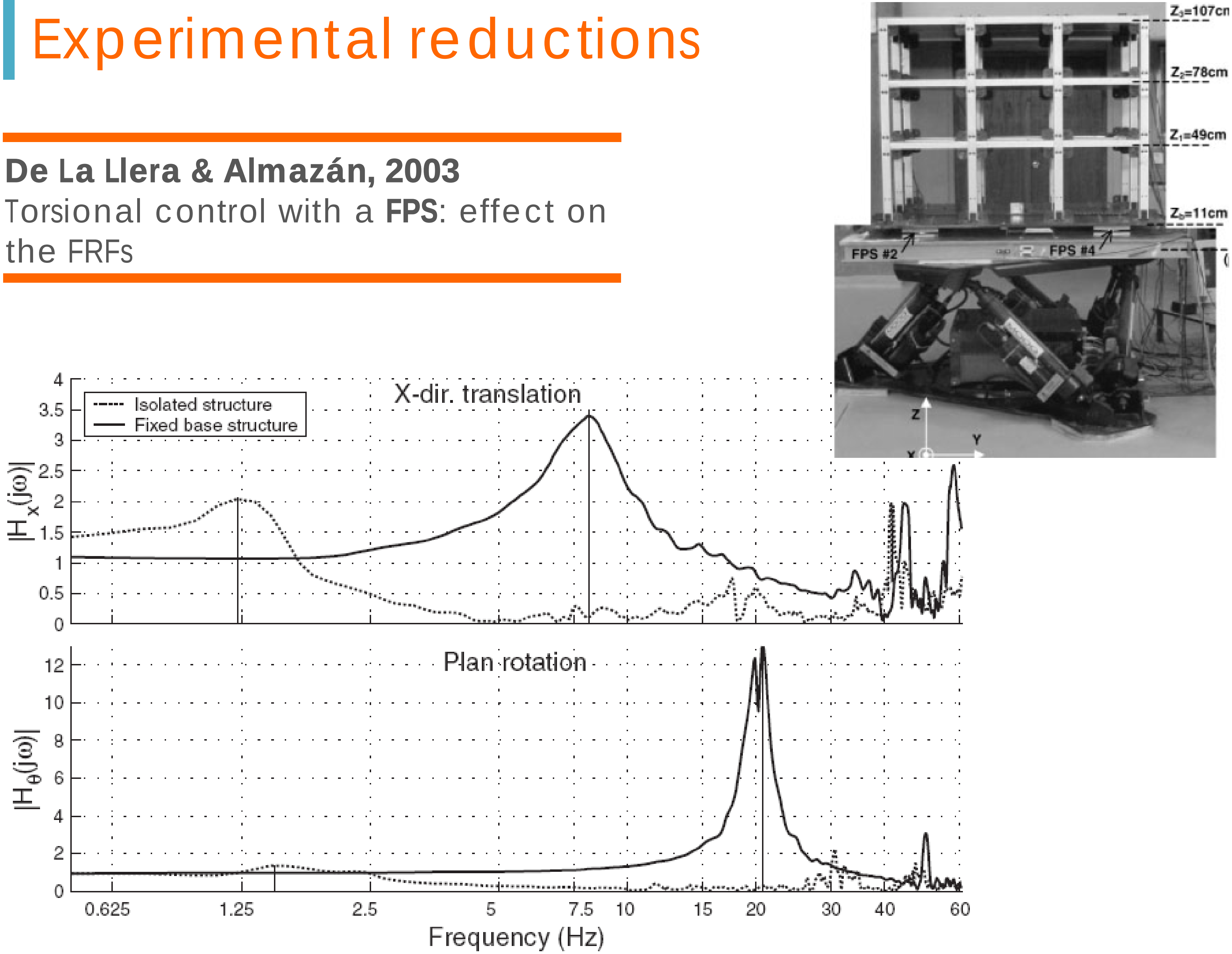
Main Collapse (12th story)

O’Higgins Tower East View

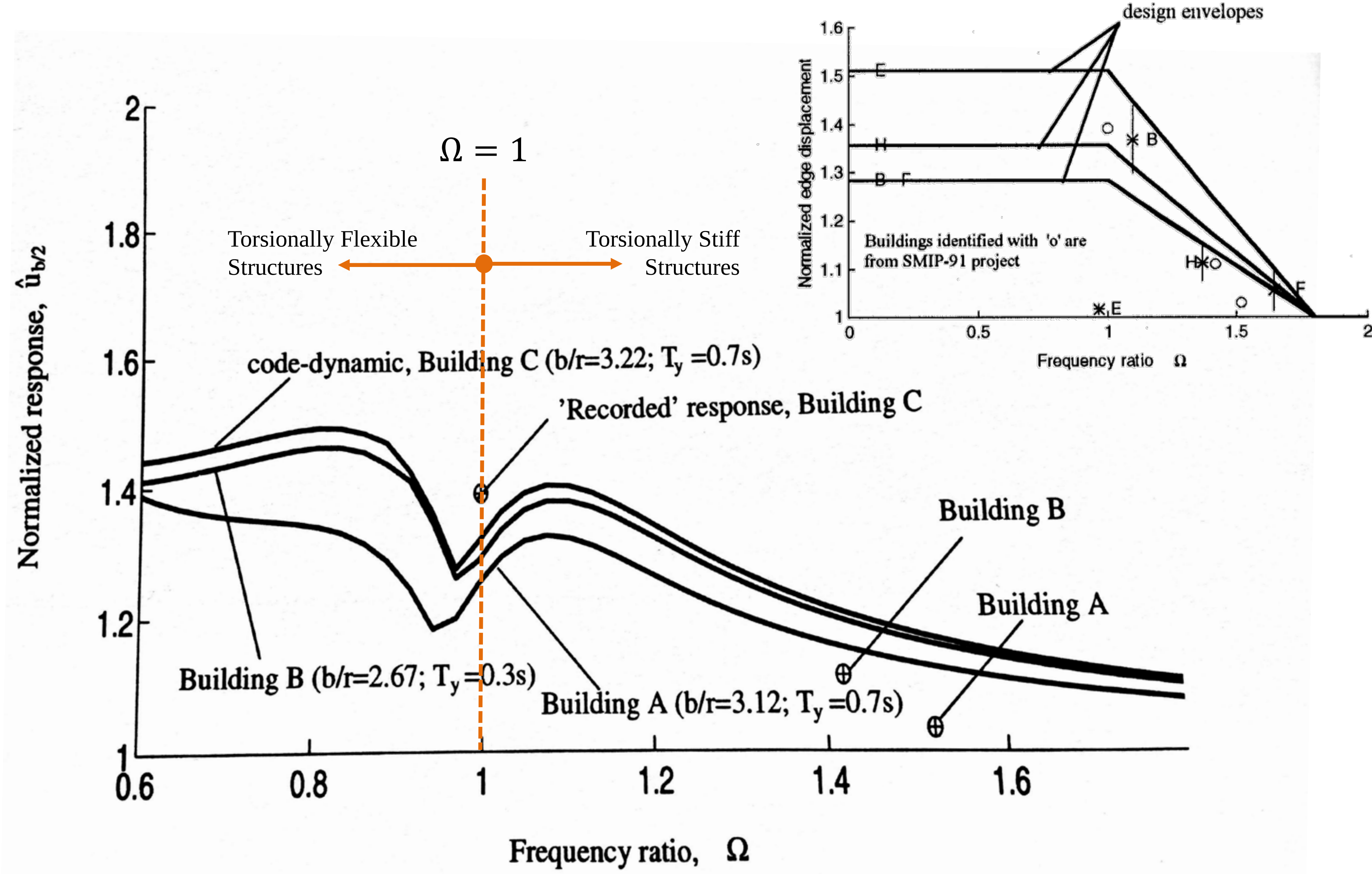
Experimental reductions

De La Llera & Almazán, 2003

Torsional control with a **FPS**: effect on the FRFs



Dynamic results vs. empirical data



$\Omega = 1$

Torsionally Flexible Structures

Torsionally Stiff Structures

Seismic Isolation

Rutenberg & Eisenberg, 1984
CR/CP of the **isolation system** below the CM of the superstructure