University of Ljubljana
Faculty of Civil and Geodetic Engineering
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RETIREMENT SYMPOSIUM AND CELEBRATION OF THE CAREER OF
Anil K. Chopra
OCTOBER 2 AND 3, 2017, SIBLEY AUDITORIUM, UNIVERSITY OF CALIFORNIA, BERKELEY

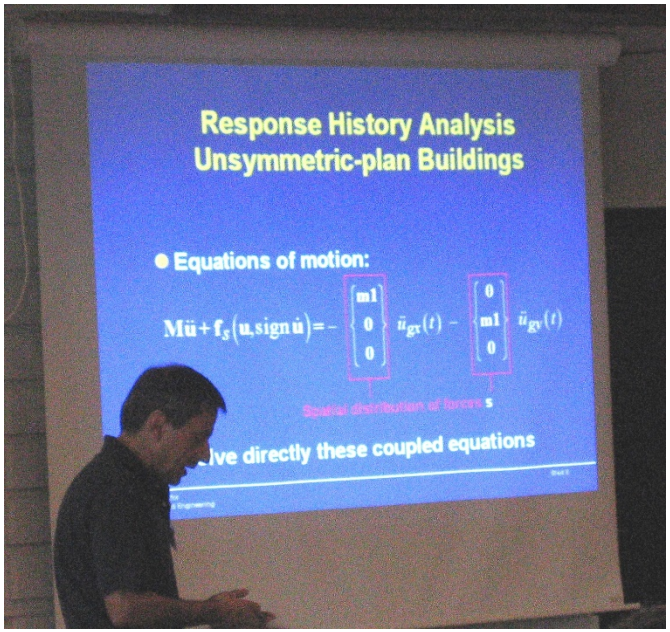
On pushover-based analysis and its adoption in Eurocode 8

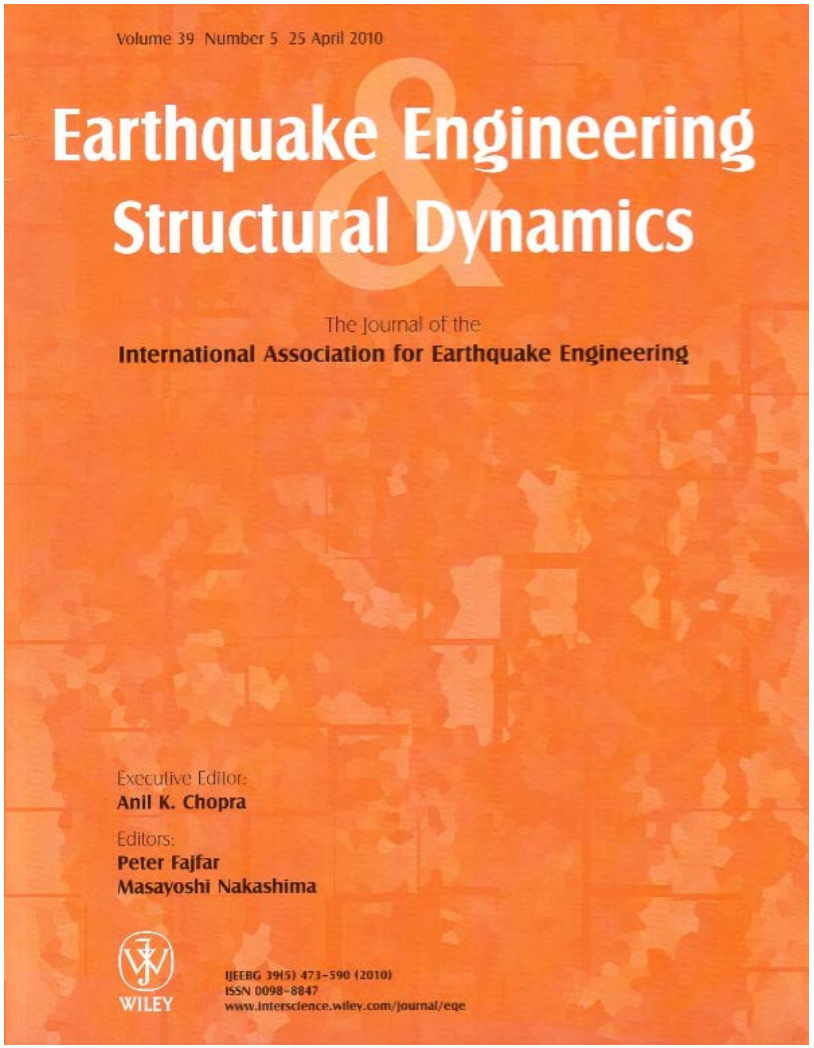
Peter Fajfar

Anil K. Chopra Symposium, Berkeley , October 2, 2017

A tribute to Anil

Bled 2011





Common topic

Pushover-based analysis

- Advocated inelastic spectra against overdamped elastic spectra
- Developed procedures for taking into account higher modes (including torsion)

Scope

- On seismic analysis
  - Response history versus pushover
- Nonlinear analysis in Eurocode 8
- Practice-oriented probabilistic analysis

Personal view,
based on 50 years of professional work
(teaching, research, consulting, code development, administration)

Seismic Analysis

Seismic response of structures is

- Dynamic
- Nonlinear
- Random

"truth … is much too complicated to allow anything but approximations"
John von Neumann (1903-1957, Hungarian-American mathematician, physicist, inventor, computer scientist and polymath)

The analysis is, at best, able to provide a reasonably accurate numerical solution to an inexact set of assumptions and highly uncertain input data

(adapted from S. Freeman)

Seismic Analysis

Nonlinear dynamic analysis is the best available tool

Irreplaceable in research and analysis of important structures

Disadvantages for practical applications

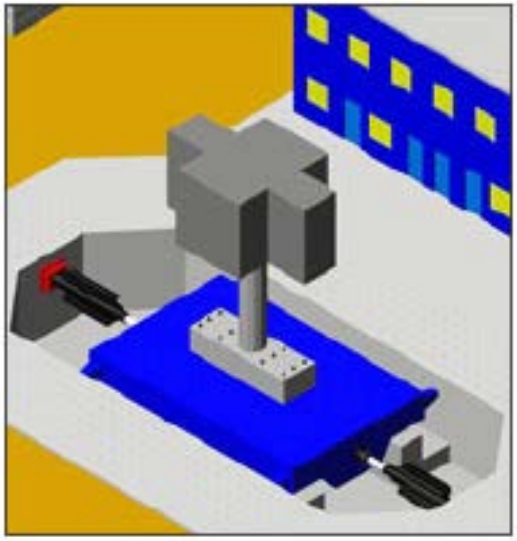
- Computationally demanding (modelling, analysis and postprocessing)
- Additional data: input ground motions, hysteretic behaviour, damping model
- Sensitivity of computed response to system parameters
- Significant judgement required
- Less transparent
- Peer review needed

The more complex the nonlinear analysis method,
the more ambiguous the decision and interpretation process is

Helmut Krawinkler

Concrete Column Blind Prediction Contest 2010

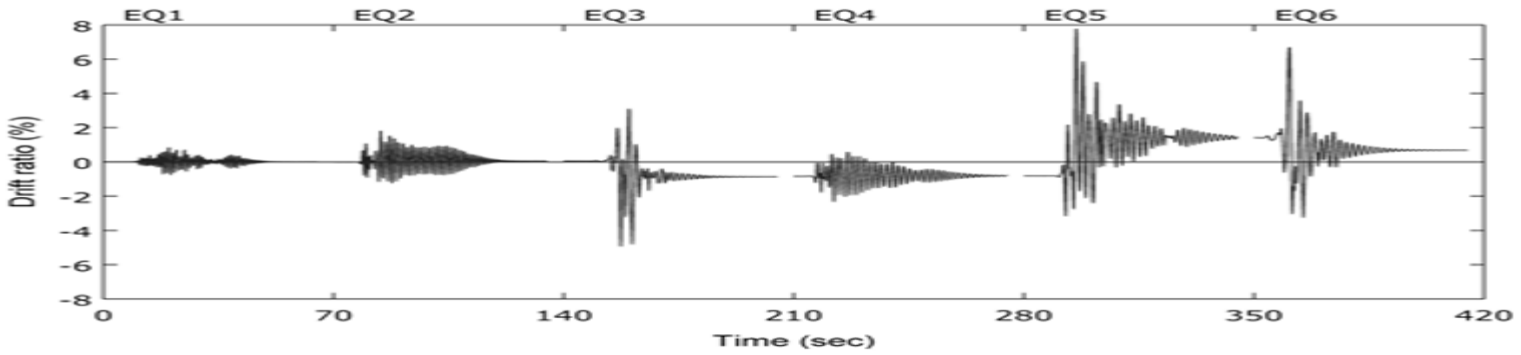
RC bridge column - PEER UCSD outdoor shaking table

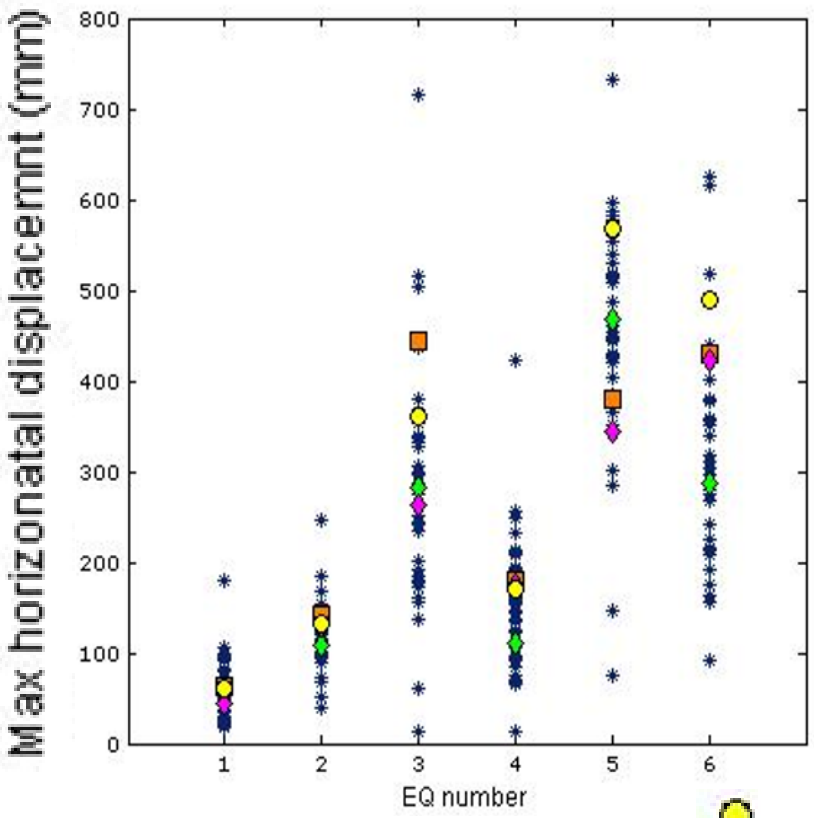


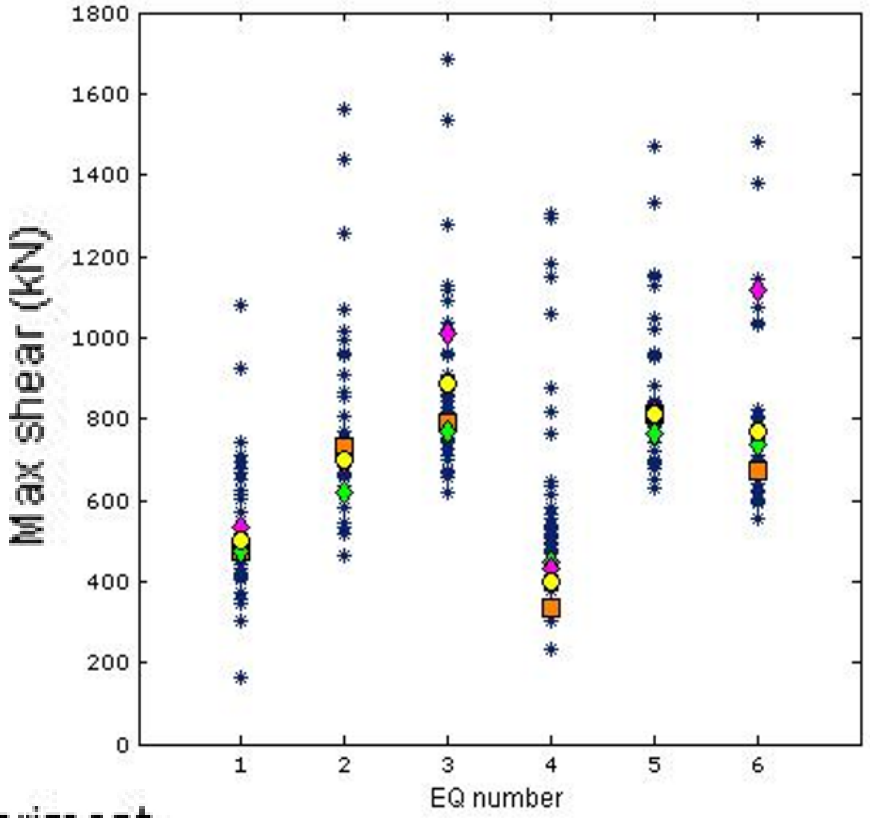
42 teams from 14 countries

http://nisee2.berkeley.edu/peer/prediction_contest/

Concrete Column Blind Prediction Contest 2010







Experiment

"Today, ready access to versatile and powerful software enables the engineer to do more and think less."

M. Sozen, A Way of Thinking, EERI Newsletter, April 2002

Future design office?

Pushover-based methods

- **Pushover** analysis of MDOF model and response spectrum analysis of SDOF model

- Provide valuable information on inelastic structural behaviour
- Are relatively simple and transparent
- Appropriate for
  - assessment of existing structures
  - checking design of new structures
  - checking the results of nonlinear dynamic analyses

- **Limitation**: structures vibrating predominately in a single mode

Nonlinear Analysis in Eurocode 8

Part 1: General and new buildings
Part 2: Bridges
Part 3: Existing buildings

Nonlinear static (pushover) analysis (NSA) and nonlinear dynamic analysis (NDA) are permitted, but not required

NSA: Basic N2 method (details in informative annex)
Warning regarding torsion and higher modes in elevation

NDA: Requirements related only to ground motion
(with exception of bridges)

Nonlinear analysis in revised Eurocode 8 (draft)

Part 1: General and new buildings
Part 3: Existing buildings and bridges
Part 2: Work has not started yet

Nonlinear static (pushover) analysis (NSA) and nonlinear dynamic analysis (NDA) are permitted, but not required

NSA: extended N2 method

NDA: requirements related only to ground motion ?

Extensions of pushover-based methods

" The nonlinear static pushover analyses were introduced as simple methods … Refining them to a degree that may not be justified by their underlying assumptions and making them more complicated to apply than even the nonlinear response-history analysis … is certainly not justified and defeats the purpose of using such procedures."

(Baros and Anagnostopoulos, 2008)

Torsion and higher modes in elevation

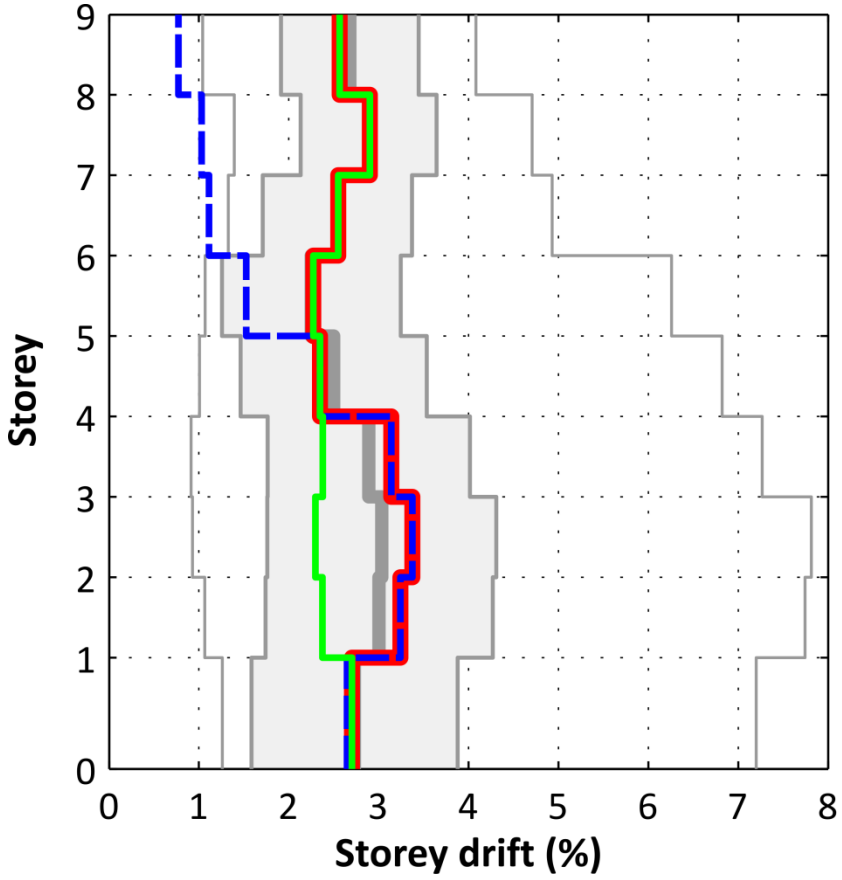
Extended N2 method

Combination of the results of two standard procedures

- Basic pushover analysis
- Elastic modal response spectrum analysis (normalized results)

Similar idea in ASCE 41 (for higher modes in elevation)

Higher modes in elevation



Nonlinear response history analysis (NRHA)

- mean
- mean ± σ
- envelope

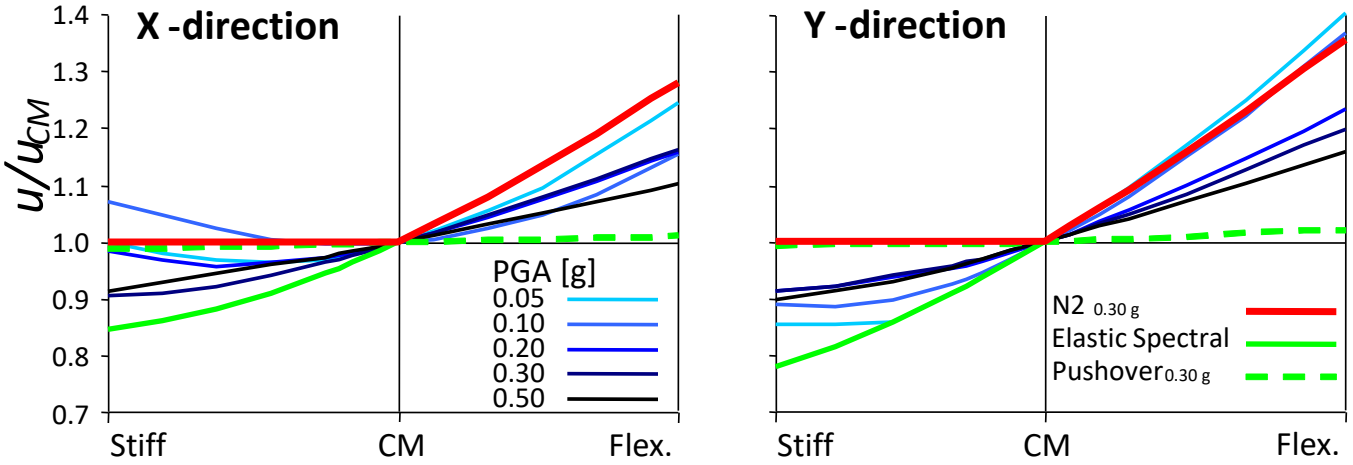
- Pushover (= Basic N2)
- Elastic modal analysis (normalized)
- Extended N2

9-storey LA building (SAC)

Kreslin and Fajfar, EESD, 2011

SPEAR building

Torsion



SPEAR building

Probabilistic Methods

Probabilistic methods have not yet found their way in engineering practice

Explicit approaches like in Appendix F in the FEMA P-695 are "too complex and lengthy for routine use in design"

(Haselton et al, 2017)

Highly simplified methods are needed

Pushover-based Risk Assessment (PRA) Method

Combination of the

- closed form SAC-FEMA probabilistic approach (Cornell et al)
- N2 method

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Probability of "failure" (NC limit state)

$$P_{NC} = \exp\left[0.5\, k^2 \beta_{NC}^2\right] H\left(S_{a,NC}\right) = \exp\left[0.5\, k^2 \beta_{NC}^2\right] k_0 S_{a,NC}^{-k}$$

P_{NC}	annual probability of "failure" (NC limit state)
k, k_0	parameters of the hazard curve
β_{NC}	dispersion measure
$S_{a,NC}$	(NC) capacity in terms of S_a

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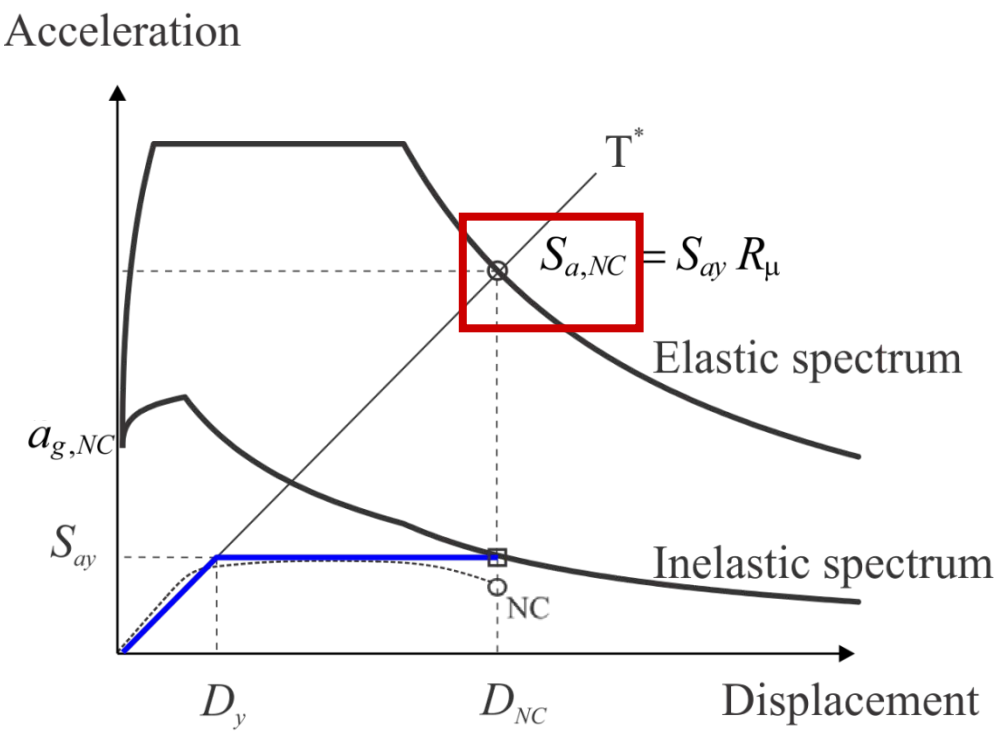
P_{NC}	annual probability of "failure" (NC limit state)
k, k_0	parameters of the hazard curve
β_{NC}	dispersion measure (predetermined values)
$S_{a,NC}$	(NC) capacity in terms of S_a (N2 method)

Determination of $S_{a,NC}$



Probabilistic Methods

Eurocode 8 – Part 1 (draft of the revised version)

Annex F (informative): Simplified reliability-based verification format

(drafted by M.Dolšek et al, based on Cornell's closed form formula for the probability of exceedance of LS)

Everything should be made as simple as possible, but not simpler